USACERL Technical Report FE-93/21
September 1993
Technology for Electrical Energy Conservation

US Army Corps of Engineers
Construction Engineering Research Laboratories

Evaluation of Potential Energy Loss Reduction and Savings for U.S. Army Electrical Distribution Systems

by
William R. Taylor

Both commercial and military electrical distribution systems inherently lose a certain amount of energy from any of several causes. This study calculated the expected range of annual energy losses that can be eliminated from typical U.S. Army electrical distribution systems to produce a savings. These calculations can help distribution engineers examine their own energy losses more carefully, and check the feasibility of other, more detailed efforts to quantify losses.

The investigation concluded that installation electrical engineers must consider the relative magnitude and sources of distribution system energy losses before initiating loss reduction measures. Some of the loss reduction methods outlined in this study produce savings that are too small to economically justify specific retrofit efforts. However, it may be feasible to incorporate the same loss reduction methods during new construction design or replacement projects.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1993	Final

4. TITLE AND SUBTITLE
Evaluation of Potential Energy Loss Reduction and Savings for U.S. Army Electrical Distribution Systems

5. FUNDING NUMBERS
4A162784
AT45
EB-XP1

6. AUTHOR(S)
William R. Taylor

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Construction Engineering Research Laboratories (USACERL)
P.O. Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER
TR-FE-93/21

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Center for Public Works (USACPW)
ATTN: CECPW-FU-E
BLDG 358
Fort Belvoir, VA 22060-5516

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

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The investigation concluded that installation electrical engineers must consider the relative magnitude and sources of distribution system energy losses before initiating loss reduction measures. Some of the loss reduction methods outlined in this study produce savings that are too small to economically justify specific retrofit efforts. However, it may be feasible to incorporate the same loss reduction methods during new construction design or replacement projects.

14. SUBJECT TERMS
electrical distribution systems
energy conservation
energy research

15. NUMBER OF PAGES
66

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

FOREWORD

This work was done for the U.S Army Center for Public Works (USACPW), Fort Belvoir, VA, under project 4A162784AT45, "Energy and Energy Conservation"; Work Unit EB-XP1, "Technology for Electrical Energy Conservation." The technical monitor was Samuel Baidoo, CECPW-FU-E.

This study was done by the Energy and Utilities Systems Division (FE), of the Infrastructure Laboratory (FL), of the U.S. Army Construction Engineering Research Laboratories (USACERL). The USACERL principal investigator was William Taylor. Research for this study was performed by Science Application International Corporation (SAIC), McLean, VA, under contract no. DACA 88-90-D-0023. Dr. David M. Joncich is Chief, CECER-FE, and Dr. Michael J. O'Connor is Chief, CECER-FL. The USACERL technical editor was William J. Wolfe, Information Management Office.

LTC David J. Rehbein is Commander and of USACERL, and Dr. L.R. Shaffer is Director.

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EVALUATION OF POTENTIAL ENERGY LOSS REDUCTION AND SAVINGS FOR U.S. ARMY ELECTRICAL DISTRIBUTION SYSTEMS

1 INTRODUCTION

Background

U.S. Army installations commonly receive electrical power through government-owned and operated distribution systems. Both commercial and military electrical distribution systems inherently lose a certain amount of energy. These energy losses may occur while energizing the system (as happens with transformer no-load losses), or as a result of resistance created by system components acting against the flow of electrical current. While energy losses can never be totally eliminated from the distribution system, by identifying their underlying causes and taking corrective measures, they can be effectively reduced to save power generation costs.

Commercial electric utilities use several methods to minimize energy losses, which are applied in varying degrees on U.S. Army electrical distribution systems:

1. Balancing three-phase loads
2. Balancing feeder circuit loads
3. Correcting the power factor
4. Optimally sizing transformers
5. Applying Conservation Voltage Reduction (CVR)
6. Sizing conductors.

The practical effectiveness of these loss reduction methods has not yet been established; it is also uncertain whether electrical losses in distribution systems are significant enough to warrant more detailed investigation. There is a need to analyze and quantify the amount of energy losses associated with electrical distribution systems, and to estimate potential savings associated with specific energy loss reduction methods.

Objective

The objective of this evaluation was to calculate the expected range of annual energy losses that can be eliminated from typical U.S. Army electrical distribution systems to produce a savings.

Approach

A literature search was conducted to determine:

- the characteristics of typical Army electrical distribution systems (Chapter 2)

- representative electrical data for different size Army installations

- different loss reduction methods, important variables affecting energy loss calculations for those methods, and their effects on other loss reduction options (Chapters 3 through 8)

- the general theory and equations required to calculate energy loss and potential savings for typical Army installations.

From this information, total annual energy losses (potential savings) expected for different size installations were calculated.

Scope

This information was produced from engineering calculations, not from instrument measurements of an actual system losses, nor from computer simulation. Energy losses were calculated based on the assumption that an entire distribution system is affected. Also, peak power usage values from the electrical data were used to calculate energy losses. These assumptions cause an overestimate of energy losses. To partially compensate for overestimates, best, worst, and nominal cases were used to associate losses with a range of probable values. The method of "partial implementation" may also be used to adjust estimated losses to a more realistic level.

Because all distribution systems are different, each must be analyzed separately before recommending a combination of loss reduction methods for a specific system. Further study may be needed for each site considering implementation of energy loss reduction methods. A study based on actual electrical measurements will allow a complete feasibility analysis to be performed before finally deciding to implement specific loss reduction strategies.

Mode of Technology Transfer

It is recommended that the results of this study be incorporated into an Engineer Technical Note (ETN).

2 OVERVIEW OF ELECTRICAL DISTRIBUTION SYSTEMS

Typical System Elements

Figure 1 shows a typical electrical transmission and distribution arrangement. Although this study was concerned only with the distribution side of the system (from the substation to the end user), an understanding of the entire transmission and distribution system is essential. The transfer of current and voltage from the generating station (utility) to the substation (on-site at Army installation) occurs through high voltage power transmission lines. The substation then takes the high voltage and steps it down to be carried by distribution lines to the distribution transformers. Finally, the distribution transformers again step down voltage to a safer level and transfer it to the loads (end user) on secondary distribution lines.

Utilities always transmit power at very high voltages so the transmission lines can be kept relatively small, to reduce costs. The typical range of transmission voltages is between 69 and 230kV. These voltages are fed into the substations, which generally operate in the 4 to 34.5kV range. This range of voltages is sent out of the substation on distribution lines to the distribution transformers, which reduce the voltage to the 120/240/480V level usually required by the consumer.

Most high voltage transmission lines are three-phase. The advantage of three-phase lines is that when the phases are balanced, the return neutral current cancels out. This allows the use of a smaller size and lower cost conductor. Three-phase lines are also convenient because individual distribution transformers, which are typically single phase, can be connected to any one of the three phases to maintain a balanced loading on the line (Figure 2).

The load density and the availability of land determines what the average distribution feeder length can be. It is important that distribution feeders not become too long because increased line (I^2R) losses will result. However, when lengthy distribution lines are required, voltage regulators are installed between the substation and distribution transformers to maintain proper voltage levels.

Generally, designers make the primary feeder voltage dependent on the overall length of the distribution system. The longer the distribution distance, the higher the distribution voltage must be. Higher voltages require less current to supply the same load. Since voltage drop (IR) and I^2R are a function of current, smaller currents reduce voltage drops and decrease system losses. Less current also permits smaller conductors to be used to transmit the same power. The smaller conductor has the advantage of a lower cost and lower weight per unit length, which results in a lower installation cost.

Switching circuits are also a standard component of distribution systems. Switching circuits on the distribution lines allows the removal of an inoperable substation and also allows the load to be transferred when necessary. When switching circuits are used to bypass an inoperable substation, the power from that substation would then be directed to, and shared among the other substations operating on the grid. More importantly, switching circuits can be used to isolate faults in the distribution system.

Representative Army Installations

Army electrical distribution systems can vary greatly in size, operational requirements, and physical layout. Therefore, the load requirements for two installations of similar geographic size can actually differ significantly.

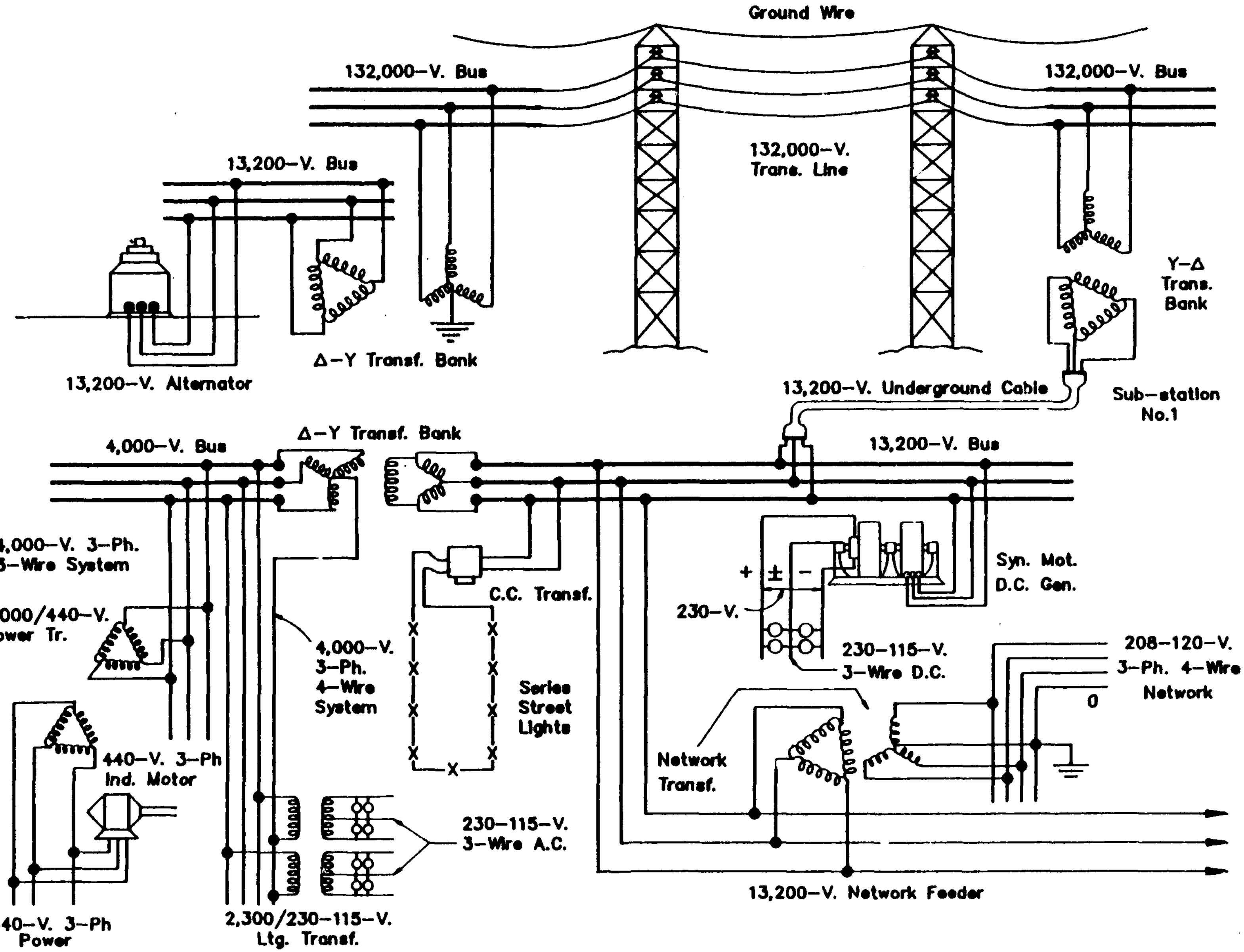


Figure 1. Typical Transmission and Distribution System.

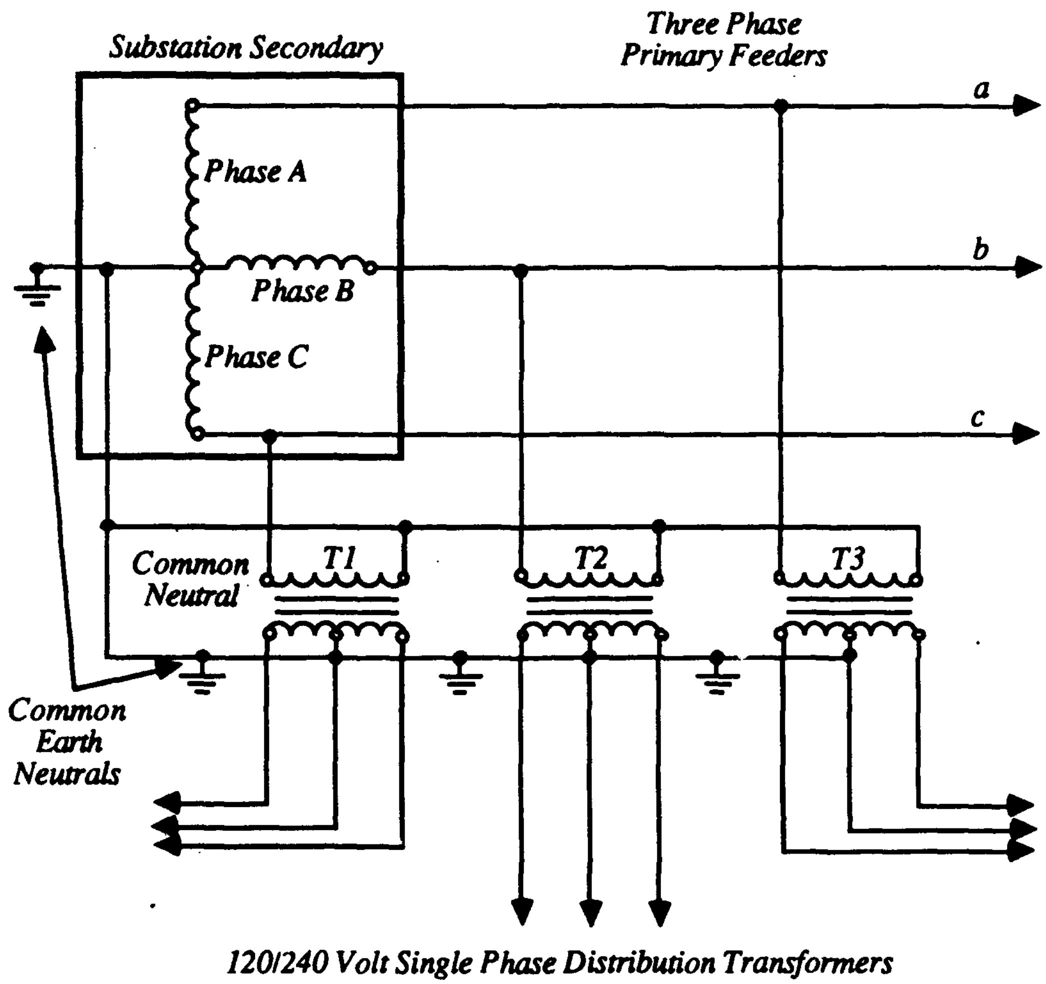


Figure 2. Typical Power Distribution System.

Table 1 illustrates these variations in terms of key electrical system characteristics for several sample installations. This information was obtained from a data base containing electrical specifications for various U.S. Army installations. These installations cover a wide range of load capacities, from 129kVA to 230MVA. The data has been grouped into installation size categories (Small, Medium, and Large) based on ranges of transformer capacity. Among each category, the average values, shown in boldfaced type in Table 1, were calculated and are used throughout this report to estimate energy losses.

Using the information in Table 1, the neutral line impedance and phase impedance data could be calculated. These values are shown in Table 2 for each size installation and are also used in this report to perform energy loss estimates.

Table 1 shows that the larger installations have the highest power capacities and also the longest distribution feeder systems. However, all sample installations had about the same average feeder lengths. This is consistent with the idea that feeder lengths not become too long.

Table 1

Representative Army Electrical Data for Different Size Installations

Description of Parameter	Small					Medium							Large			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Base substation transformer capacity (kVA)	129	245	698	11231	17674	44876	45038	48497	54942	56306	60719	63778	83321	104609	122435	230002
Average substation transformer capacity (MVA)	6					54							135			
Base substation and distribution station quantity	3	17	8	1	0	18	1	8	1	12	15	8	3	5	18	8
Total base distribution length (miles)	168	238	414	96	90	114	80	330	135	764	414	524	293	439	222	558
Average total distribution length (miles)	201					337							378			
Number of feeders per base	4	5	6	5	5	9	10	10	10	10	10	11	15	20	20	25
Average number of feeders per base	5					10							20			
Overall average feeder length (miles)	4					4							4			

Table 1 (Cont'd)

Description of Parameter	Small					Medium							Large			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Primary line-to-line feeder voltage (V)	13200	13200	-	12500	12470	34500	13200	-	-	-	34500	12000	4800	13200	7200	12500
Primary line-to neutral feeder voltage (V)	7621	7621	-	7217	7200	19919	7621	-	-	-	19919	6928	2771	7621	4157	7217
Average line-to-neutral voltage (kV)	7					14							5			
Number of single phase distribution transformers	84					421							1253			
Average capacity of 3-phase distribution transformers (kVA)	50					50							50			
Peak power use 1989 (MW)	1	4	3	3	9	10	14	-	14	22	42	-	92	30	51	69
Average peak power user (MW)	4					20							60			

Table 2

Neutral Line Impedance and Phase Impedance Data

Description of Parameter	**Sample Installation**		
	Small Base	**Medium Base**	**Large Base**
P_p Total average peak power(MW)	4.0	20	60
$S_p = P_p/.95$ Total average peak apparent power (MVA) at pf 95	4.2	21	63
Average peak power per feeder per phase (kW)	267	667	1,000
Average peak apparent power per feeder per phase (kVA at pf 95 %)	281	702	1,053
Magnitude of peak effective current per feeder per phase I_a(A)	38.10-j12.52 Mag = 40	47.62-j15.65 Mag = 50	200.0-j65.72 Mag = 211
$Z_n = 2Re(Z_1)+Im(Z_1)$ Neutral line impedance (Ω/Mile)	6.94+j0.66	5.50+j0.65	0.70+j0.50
$Z_0 = Z_n$ Lf Neutral line impedance (Ω)	13.88+j1.32	11.00+j1.30	1.40+j1.00
$Z_{Aa} = Z_{Bb} = Z_{Cc}$ Total phase impedance (Ω)	165.8+j54.49 Mag -174.5	265.3+j87.19 Mag = 279.3	22.56+j7.41 Mag = 23.75
$Z_a = Z_{Bb} = Z_c$ Load phase impedance (Ω)	152.0+j51.85	254.3+j84.59	21.16+j5.41
$Z_A = Z_B = Z_C = Z_f$ Total feeder impedance (Ω)	13.88+j2.64 Mag = 14.13	11.00+j2.60 Mag = 11.30	1.40+j2.00 Mag = 2.44
$Z_f = Z_f$ Lf Total feeder impedance (Ω)	13.88+j[illegible]	11.00+j2.60	1.40+j2.00
Z_1 Line impedance (Ω)	3.47+j0.66	2.75+j0.65	0.35+j0.50

As stated above, all calculations are based on the average peak power values shown in Table 1. The average peak power usage is the highest MW value of electrical power drawn from the utility during any single time during the year. Note that using the peak power value for calculations will cause loss estimates to be higher than the actual energy losses; for specific applications estimates should be adjusted accordingly.

3 BALANCING PHASE LOADS ON THREE-PHASE SYSTEMS

Description

When the loading on each of the phases of a three-phase distribution feeder is not equal, the load is described as unbalanced. Part of this imbalance may be due to many single phase lines being tapped from the same phase along the feeder. If these single phase taps are redistributed among the three phases to produce a balanced load, energy losses can be reduced.

Balancing loads among the three phases reduces distribution I^2R in two ways. First, the electrical current in the neutral conductor, which provides a return circuit path for any current imbalance, is reduced. Theoretically, if the three phases are exactly balanced, the neutral current is zero because the sum of the three phase currents (120 degrees out of phase but equal in magnitude) is zero. Secondly, I^2R for all three phase conductors is reduced because, for a given three-phase loading, the sum of the phase currents squared is minimized when the three-phase currents are equal.

Figure 3 shows the typical phase load condition where the three load impedances (Z_a, Z_b, and Z_c) are unbalanced. It also shows the equal conductor line impedances (Z_A, Z_B, and Z_C), which cause excessive distribution line power losses (I^2R) when the system is unbalanced. An additional impedance (Z_o), which represents the neutral line impedance, must also be considered. In an unbalanced state, current is forced through the neutral line, resulting in a voltage drop across it. This voltage drop causes a dissipation of power (energy loss) in the neutral line.

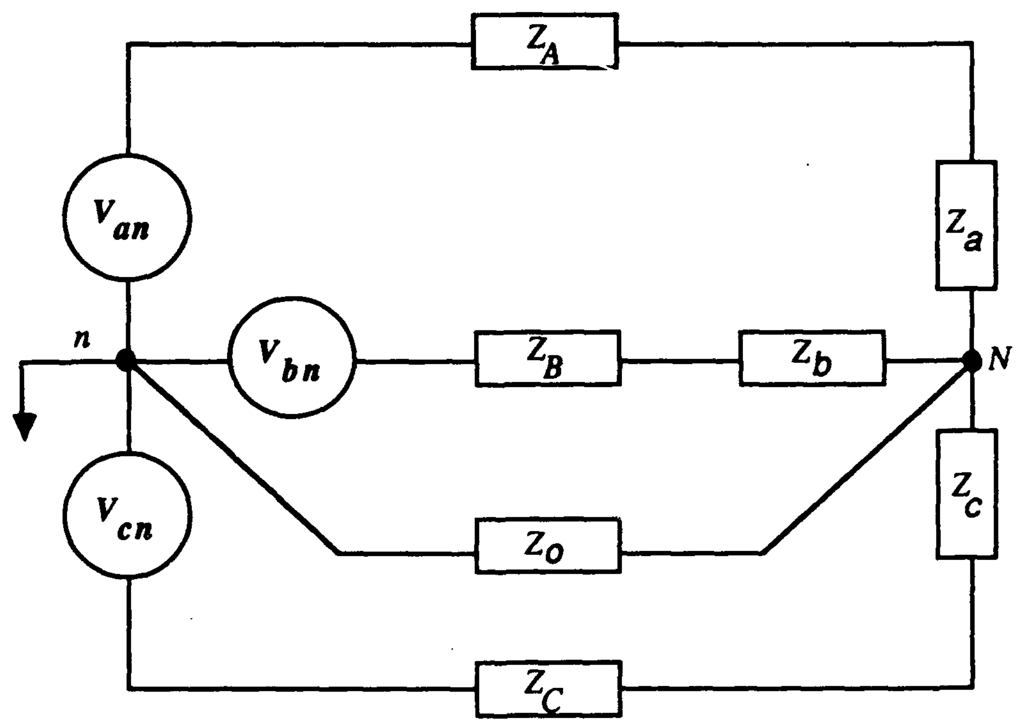


Figure 3. Unbalanced Three-Phase Load Condition ($Z_a \neq Z_b \neq Z_c$).

The following section identifies the parameters and presents energy calculations for reducing losses by balancing phase loads, and shows a sample calculation of losses for "typical" (assumed) feeder conditions. Energy loss estimates for different size Army installations are also presented and discussed.

Key Parameters

The following parameters describe the variables that must be considered when analyzing three-phase loads.

Imbalanced Current

All electrical conductors have some resistance to the flow of electricity, which creates power losses proportional to the current squared. As stated above, when phase currents are imbalanced, power losses increase both in the phase conductors and neutral conductor.

Load Distribution

Load distribution for a system can vary greatly depending on size of the base and load locations. Both single-phase and three-phase loads are connected at various distances along the feeder. Electrical current to supply each of the loads must be carried the length of the conductor that is "upstream" toward the power supply. Thus, the amount of total current, as well as the imbalanced current, will vary along the length of the feeder. To simplify this real world condition to permit calculation of estimated losses, it is assumed that the loads on the feeder are evenly distributed; the entire load is assumed to occur at the midpoint of the feeder. If the feeder has loads concentrated toward the end of the feeder, losses will be greater; the assumptions will cause an underestimate of losses. For feeders with loads concentrated at the front of the feeder, the assumptions will cause an overestimate of losses.

Types of Loads

Loads found throughout the electrical distribution system are largely inductive. These inductive loads are characterized by the fact that they require two components of current. One of these is the reactive or magnetizing current necessary to magnetize the iron cores found in inductive type loads. The other component of current, termed the real or actual current, is the component of current that does the useful work. These two components of current are in quadrature (they are orthogonal) with each other, therefore the total current drawn by the load will equal their vector sum.

Apparent and Actual Power

The useful or actual power in an electric circuit is generally measured in terms of kilowatts (kW) and the reactive power in terms of kilovars (kVAR). Because these two quantities are produced by the actual current and reactive current respectively, they have exactly the same vector relationship as the components of current. This means that the total or apparent power (measured in terms of kVA) can also be calculated vectorially.

Conductor Size

Conductor size directly affects the amount of feeder I^2R. The conductor line impedance (Ω/Mile) is the actual parameter that relates to the conductor size and is needed to calculate energy losses. Impedance varies inversely with conductor size, which means that smaller size conductors have greater impedance to the flow of current and therefore greater losses.

Feeder Length

To calculate the total feeder impedance of the conductors, feeder length is multiplied by the conductor's impedance per unit length (found in standard conductor tables). Obviously, longer feeders have greater losses.

Power Factor

Since the considered losses are due to current imbalance, three-phase loads that change the power factor equally on all three phases do not affect the current imbalance. However, for single-phase loads with poor power factor, the phase carrying the load is burdened with extra current due to the poor power factor. Therefore, single phase loads with poor power factors are contributing additionally to the imbalanced current problem. A 95 percent power factor is assumed constant for distribution system calculations in this report (except for Chapter 5).

Ambient Temperature

Ambient temperature also affects the impedance of metal conductors. Impedance increases with temperature. For all calculations in this report, variation of impedance due to temperature is ignored. The impedance per unit length values used assume an ambient temperature of 25 °C (77 °F).

Methodology for Determining Energy Savings

To develop the calculations needed to estimate energy losses due solely to the imbalance in phase currents, the two major sources of power loss in an unbalanced three-phase circuit were considered: distribution line loss and neutral line loss. The following procedure describes the method used to determine those energy losses.

Calculate Neutral Line Impedance

Impedance is of great importance because it directly affects the amount of neutral line power loss in the system. Since most Army three-phase loads are distribution transformers spread out over a great distance, it becomes necessary to find the average feeder distance from the substation to the distribution transformers. This is done by dividing the average feeder length by two. This method will ensure reasonable results since some distribution transformers are relatively close to the substation while others are a greater distance away. The neutral line impedance per unit length is calculated assuming the neutral line to be approximately one half the size of the phase conductors. Equation 1 is used to calculate the neutral line impedance:

$$Z_o = \frac{Z_n L_f}{2} \qquad \text{[Eq 1]}$$

where:

Z_o	=	Average neutral line impedance	Ω
Z_n	=	Neutral line impedance per unit length	Ω/Mile
L_f	=	Average feeder length	Mile

Calculate Total Load and Line Impedance

The total load and line phase impedances, Z_{Aa}, Z_{Bb}, and Z_{Cc}, must be calculated assuming a balanced state. To do this, the effective line-to-neutral voltage squared is multiplied by three times the number of feeders and divided by the total average peak apparent power (volt-amperes). The number "3" converts the term to a per-phase basis, as shown Equation 2. The subscripts indicate that this equation is applicable for all three phases:

$$Z^{*}_{Aa,Bb,Cc} = \frac{3\ N_f\ |V_{abcn}|^2}{S_p} \qquad \text{[Eq 2]}$$

where:

$Z_{Aa,Bb,Cc}$	=	Total load and line phase impedance	Ω
N_f	=	Average number of feeders	-
S_p	=	Total average peak apparent power per base	VA
V_{abcn}	=	Effective line-to-neutral phase voltage	V

Calculate Neutral Line Peak Apparent Power Loss

Equation 3 accounts for both real and reactive power losses results, which is equal to the apparent power lost or dissipated in the neutral conductor when the three-phase loads are unbalanced. Equation 3 was derived by applying the techniques of circuit analysis (Kirchhoff's Current Law) on the circuit in Figure 3. Ideally, the power loss calculated would be equal to zero when all three loads are balanced in magnitude and phase. In other words, the real and reactive power consumption of each phase is exactly the same.

$$S_n = (Z_o)\left|\frac{V_{an}Z_{Bb}Z_{Cc} + V_{bn}Z_{Aa}Z_{Cc} + V_{cn}Z_{Aa}Z_{Bb}}{Z_{Aa}Z_{Bb}Z_{Cc} + Z_oZ_{Aa}Z_{Bb} + Z_oZ_{Aa}Z_{Cc} + Z_oZ_{Bb}Z_{Cc}}\right| \qquad \text{[Eq 3]}$$

where:

V_{an}	=	Phase A, line-to-neutral effective voltage	kV
V_{bn}	=	Phase B, line-to-neutral effective voltage	kV
V_{cn}	=	Phase C, line-to-neutral effective voltage	kV
Z_{Aa}	=	Phase A, total load and line impedance	Ω
Z_{Bb}	=	Phase B, total load and line impedance	Ω
Z_{Cc}	=	Phase C, total load and line impedance	Ω
S_n	=	Peak apparent power loss of neutral line per feeder	VA

Calculate Effective Phase Currents

Another power loss that needs to be calculated is the extra power lost in the distribution lines when the load impedances are unbalanced. Ideally, when the system is balanced, all the phase currents are equal in magnitude. This represents the point of minimal power loss and, for calculation purposes, it will be considered zero power loss. To calculate the power lost in the distribution lines when the loads are

unbalanced requires that the phase currents be calculated initially. Applying the techniques of circuit analysis to Figure 3 yields Equation 4:

$$I_{a,b,c} = \frac{V_{abcn}}{Z_{Aa,Bb,Cc}} \quad \text{[Eq 4]}$$

where:

$I_{a,b,c}$	=	Peak effective phase current	A

Determine Conductor Impedance

The impedance per unit length of the phase conductors is selected from standard engineering tables. The impedance per unit length is multiplied by the conductor's average feeder length to determine the conductor's impedance.

Calculate Conductor Line Peak Apparent Power Loss

After calculating the phase currents, the power lost in the distribution line can now be calculated using Equation 5. Note that Equation 5 calculates the power lost in the distribution lines with regard to the fact that the distribution lines dissipate power even when the system is balanced. Therefore, to calculate the extra power dissipated in the distribution lines, when the system becomes unbalanced, it is necessary to find the difference in power dissipation between a balanced and an unbalanced condition. Equation 5 shows that the line or conductor impedance of all the phases is divided by two to estimate the average distance the current will travel in the feeder.

$$S_l = \frac{|I_a|^2 Z_A + |I_b|^2 Z_B + |I_c|^2 Z_C - 3|I|^2 Z_{A,B,C}}{2} \quad \text{[Eq 5]}$$

where:

S_l	=	Peak apparent power loss of conductors per feeder	VA
$Z_{A,B,C}$	=	Line phase impedance $Z_{A,B,C} = Z_t$	Ω
I	=	Peak effective phase current any balanced phase	A
$I_{a,b,c}$	=	Peak effective unbalanced phase currents	A

Calculate Total Percent Power Loss

Equation 6 is used to calculate the percent loss of power due to a three-phase unbalanced condition. This equation calculates percents on a 100 percent scale. According to Equation 6, if all the phase impedances are the same and all three line-to-neutral voltages form a perfect set of three-phase voltages (equal in magnitude and 120 degrees out of phase), then the percent decrease in power would be equal to zero. On the other hand, there may be significant power losses if the difference between phase impedances is substantial.

$$\%\,\text{Power Loss} = \frac{N_f (S_l + S_n)}{S_p}\, 100 \quad \text{[Eq 6]}$$

Calculate Annual Energy Loss Per Feeder

To find the annual energy loss (Equation 7) in terms of kWh requires the apparent power loss term ($S_l + S_n$) used in Equation 6 to be multiplied by the number of hours in a year and a percent loading factor. The energy loss term is in Watt-hours, therefore it must be divided by 1000 to convert it to kWh. The percent loading factor for this report is assumed to be 50 percent or 0.5.

$$E = \frac{(8760)\,(0.5)\,\mathrm{Real}\,(S_l + S_n)}{1000} \qquad \text{[Eq 7]}$$

where:

E = Annual energy loss per feeder kWh/yr

Example Problem (Chapter 3)

An assessment of the power lost in the distribution lines of a three-phase feeder is required. Assume that the loads are evenly distributed along the feeder's length. Use the parameters given in Table 3 and calculate the I^2R and annual kilowatt-hour (kWh) energy loss in each leg of the feeder. All assumptions used to derive the equations above are applicable here, and the results are shown in Table 4.

Application Considerations

Using the methodology for determining energy savings, annual energy losses due to unbalanced three-phase loads were calculated for different size Army installations. The results are presented graphically in Figure 4 and numerically in Table 5.

These results were divided into three different size installations (small, medium, and large) for comparison. To distribute the results into three different categories, electrical distribution system data and selected schematic drawings from random Army installations were used (Table 1, p 12). The neutral line impedance and phase impedance parameters were calculated from this information. Particular information for neutral and phase impedance parameters is listed in Table 2 (p 14). The information contained in both Tables 1 and 2 is used throughout this report for performing Army installation energy loss calculations.

Table 3

Power System Parameters for Example Problem (Chapter 3)

Parameters	Measure
Conductors	2/0 AWG bare copper
Percent loading	50 percent
Power factor	95 percent
Effective voltage	12,470/7,200 V
Impedance of conductor at 25 °C	0.44+j0.53 Ω/Mile

Table 4

Results For Example Problem (Chapter 3)

Total Feeder Length (Mile)	A = 90,B = 90,C = 90		A = 100,B = 90,C = 90		A = 120,B = 90,C = 90	
	I^2R Loss (kW)	Energy Loss (kWh/Yr)	I^2R Loss (kW)	Energy Loss (kWh/Hr)	I^2R Loss (kW)	Energy Loss (kWh/Yr)
1	5.35	23,415	5.80	25,425	7.10	31,084
3	16.04	70,246	17.40	76,202	21.13	92,566
5	26.73	117,077	28.97	126,906	35.01	153,358

Phase (A, B, or C) - Phase Amps (at Supply)

The results from Table 4 show that each size installation had some noticeable energy losses; however the large bases produced higher energy losses at all degrees of imbalance. This implies that the larger bases would have a greater potential for higher energy savings. The best explanation for this is that the large sample installations included in this study generally had higher feeder currents.

The data presented in Table 5 show values for the annual energy losses in kWh as well as the associated percent power loss. Note that these values are really the additional energy loss due solely to the unbalanced phase conditions; they do not include the losses associated with the balanced load condition. In other words, the value is not the total energy loss expended. Note that, in the example problem above, the values shown for annual energy loss are actually the total energy loss, including the balanced condition losses. For example, in a case that has I=120A and a 5-mile feeder length,* from the example values shown in Table 4, the difference in annual energy expenditures for the unbalanced case (33 percent unbalance) and the balanced case (0 percent unbalance) is 153,358 − 117,077 = 36,281 kWh/yr. This means that the 36,281 kWh/yr is the additional energy loss due solely to the phase load imbalance. Also, it should be pointed out that the 33 percent unbalance noted above was determined by dividing the additional 30A above the balanced condition by the 90A balanced condition.

This means that keeping three-phase loads balanced will minimize energy losses no matter what size load, thereby increasing the efficiency of the distribution system. The calculated results clearly showed that substantial energy savings can be achieved, especially in cases of higher imbalance conditions. Implementation of this option merely requires doing periodic checks on feeders to determine imbalances and simply shifting loads from overloaded phases to create a better balance among the three phases. This will ensure optimum system efficiency and will keep energy losses as low as possible. As stated previously, a low power factor for single-phase loads contributes an additional burden on the phase carrying the load and is a problem that needs to be considered when calculating energy losses. The final consideration that must be addressed is the actual ambient temperature the system is operating in. This study assumes a constant ambient temperature of 25 °C; however, if the system continually operates in a high temperature environment, the energy loss calculations should allow for a higher estimate of losses than those shown in this report.

* 1 mi = 1.61 km.

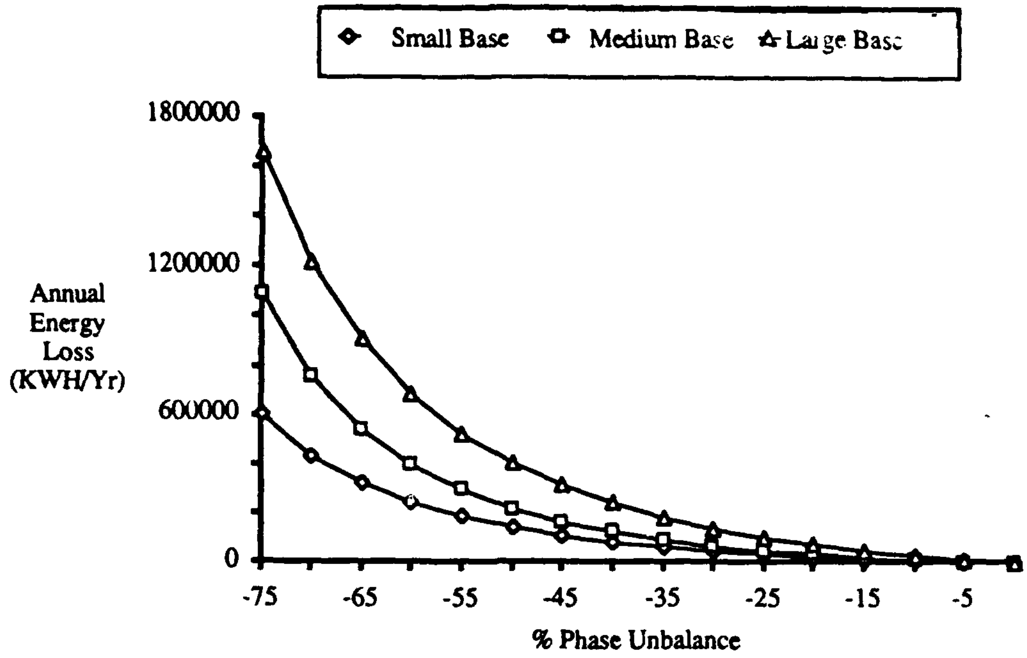


Figure 4. Annual Energy Loss vs. Percent Unbalance (Per Feeder).

Table 5

Annual Energy Loss for Three-Phase Load Unbalance (Per Feeder)

	Small Base		Medium Base		Large Base	
% Phase Unbalance	**% Power Loss**	**Energy Loss (kWh/Yr)**	**%Power Loss**	**Energy Loss (kWh/Yr)**	**% Power Loss**	**Energy Loss (kWh/Yr)**
-75	16.60	603,943	12.12	1,097,379	19.19	1,663,742
-70	12.80	439,536	8.42	761,905	14.10	1,219,293
-65	9.00	327,358	6.03	545,923	10.58	911,897
-60	6.81	247,810	4.42	399,942	8.06	691,991
-55	5.22	189,666	3.29	297,530	6.21	530,330
-50	4.02	146,120	2.47	223,529	4.81	408,802
-45	3.11	112,847	1.87	168,774	3.74	315,733
-40	2.39	86,999	1.41	127,465	2.90	243,336
-35	1.83	66,636	1.06	95,794	2.23	186,271
-30	1.39	50,401	0.79	71,186	1.70	140,780
-25	1.03	37,327	0.59	51,853	1.27	104,165
-20	0.74	26,707	0.41	36,520	0.91	74,449
-15	0.50	18,015	0.27	24,268	0.62	50,163
-10	0.30	10,857	0.16	14,416	0.37	30,194
-5	0.14	4,930	0.07	6,456	0.17	13,693
-0	0.00	0	0.00	0	0.00	0

4 BALANCING FEEDER CIRCUIT LOADS

Description

This chapter analyzes energy losses caused by unbalanced feeder circuit loads, when two feeders form a loop separated by a normal open switch. Assuming the open switch point along the loop could be changed to maintain equal loading on both feeders, energy losses could be reduced by keeping the feeder loads balanced. Operating a distribution system with unbalanced feeder circuit loads increases the total conductor line (I^2R) losses within the system. Energy losses that are attributable to feeder circuit load imbalance are analogous to the situation of unbalanced three-phase loads discussed in Chapter 3. To analyze feeder circuit load imbalance, a loop feeder arrangement is assumed (Figure 5). The amount of unbalance or I^2R losses will vary depending on the actual location of the open point in the loop. Though this option is analyzed from the standpoint of a looped feeder arrangement, these results can also be applied to separate parallel feeders with different lengths and load characteristics.

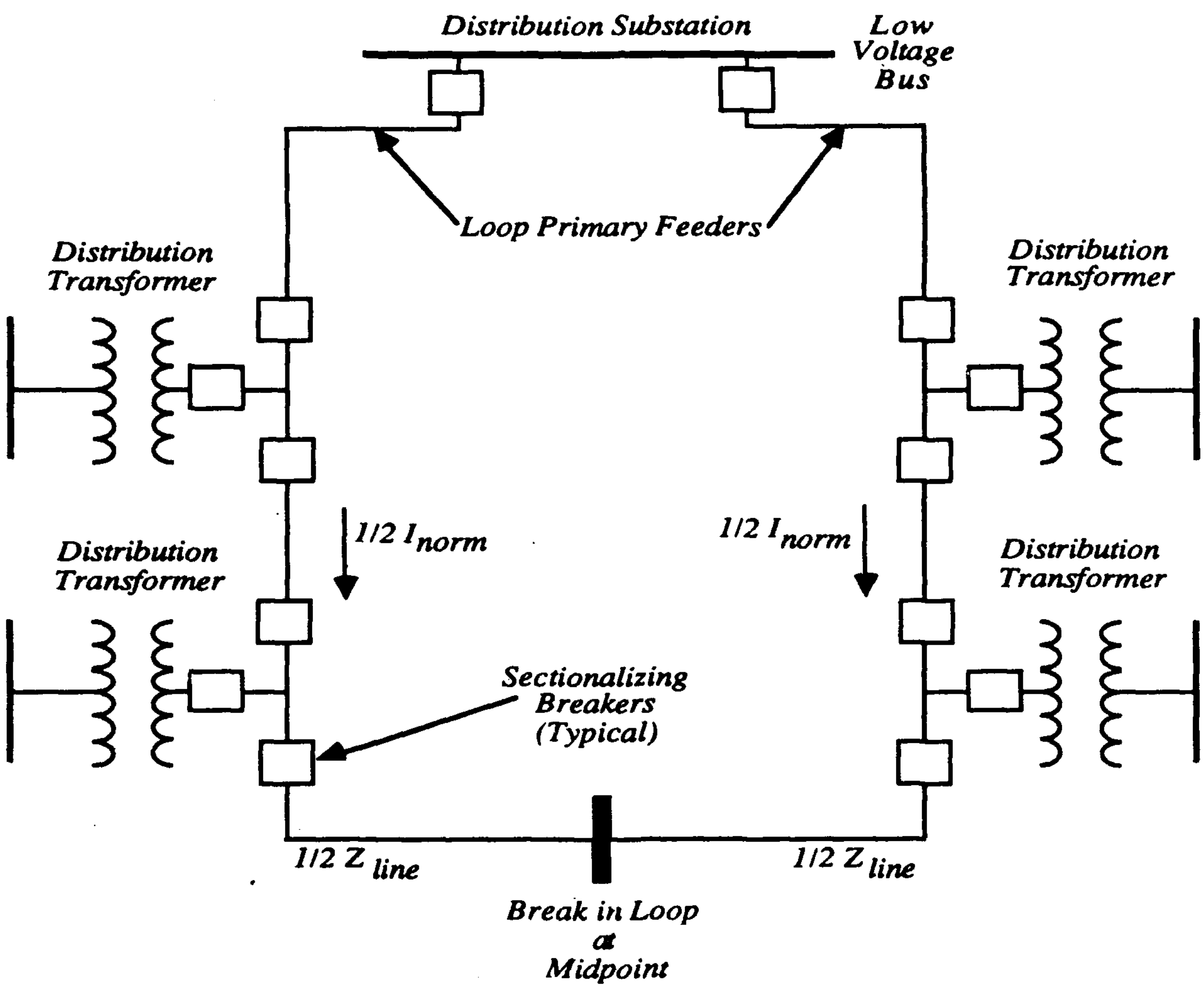


Figure 5. Loop Form of the Primary Feeder.

From a standpoint of energy loss (and assuming an even load distribution along the loop), if open point occurs near the center of a loop feeder system, then the resulting two feeders would be of equal length and no additional I^2R losses would result. However, if the open point occurred at the substation (a worst case scenario), then the result would be one long feeder supplying all loads. In this situation, a quadrupling of line losses (I^2R) would occur.

Key Parameters

The following parameters are considerations when calculating energy losses for unbalanced feeder circuit loads.

Open-point Location

This location identifies where the looped feeder circuit has been switched open. To perform an energy loss analysis, designations were assigned to various locations around the loop feeder. The assumptions made for location values are that the substation is designated as location zero (0.00), the midpoint of the loop is one-half (0.50), and returning back to the substation again is location one (1.0).

Load Distribution

The effect that load distribution had on three-phase circuits is the same for feeder circuit loads. Again, it is assumed that the feeder loads are evenly distributed.

Types of Loads

Inductive loads discussed in Chapter 3, **Key Parameters** have the same effect on feeder circuit loads.

Apparent and Actual Power

These terms were discussed in Chapter 3, **Key Parameters**.

Conductor Size

The conductor size determines the amount of impedance the conductor has. Therefore, as stated in Chapter 3, conductor impedance has a great impact on the amount of energy losses for feeder circuits.

Feeder Length

Feeder lines have distribution line (I^2R) losses along their entire length; therefore the voltage continually is being reduced as it travels the feeder line.

Ambient Temperature

Temperature change was ignored for calculations in this study. A constant ambient temperature of 25 °C is assumed.

Methodology for Determining Energy Savings

This section discusses the methodology and presents the calculations used to determine the amount of energy losses that result from unbalanced feeder loads.

Calculate Normal Peak Apparent Power Loss

Before a change in the open point occurs, the circuit in Figure 5 operated as two separate feeders with half the current $I_{norm.}$ being delivered through each half of the loop. This assumes that the distribution transformers are evenly spaced around the loop. Each of these currents sees one-fourth of the line impedance $Z_{A.}$ Equation 8 is derived from this theory, and calculates the total power dissipated in the looped feeder. Again, one-half of the feeder distance is used to approximate even distribution.

$$S_{norm} = 2\left|\frac{I_{norm}}{2}\right|^2 \frac{Z_A}{4} \qquad \text{[Eq 8]}$$

where:

S_{norm}	=	Normal peak apparent power loss per phase	VA
I_{norm}	=	Normal peak effective phase current	A
Z_A	=	Line phase impedance of loop-feeder $Z_A = Z_t$	Ω

Calculate Segmented Feeder Peak Apparent Power Loss

After a open-point change occurs, the substation must still supply the same loads with the same amount of current or load. Therefore the current in the segmented loop must be equal to the current before the change, $I_{norm.}$ When there is a break in the loop, two individual feeder circuits, which must be analyzed separately, result. To calculate the power losses, Equation 8 must be separated into two equations, Equations 9 and 10, so that the line impedance and line current reflect the location of the open-point. Loads are assumed to be located symmetrically around the feeder loop. The power loss can then be calculated as a function of open-point distance around the loop. Open-point locations, as stated in the **Methodology for Determining Energy Savings** (above) are assigned as a percentage of distance around the loop feeder, assuming one complete cycle of the loop is equal to one.

$$S_{fault1} = \frac{|I_{norm} D_f|^2 Z_A}{2} \qquad \text{[Eq 9]}$$

$$S_{fault2} = \frac{|I_{norm}(D_f - 1)|^2 Z_A(D_f - 1)}{2} \qquad \text{[Eq 10]}$$

where:

D_f	=	Distance around feeder loop from 0 to 1	Ω
S_{fault1}	=	Peak apparent power line loss per phase of section 1	VA
S_{fault2}	=	Peak apparent power line loss per phase of section 2	VA

Calculate Total Percent Power Loss

Normal power loss must first be calculated using Equation 8. The normal power loss is then subtracted from the sum of the two changed open-point power losses that were calculated using Equations 9 and 10. Then it is multiplied by three times the number of feeders. Next, the resulting value is divided by the total average peak apparent power per base. The percent power loss due to a changed open-point in the looped feeder can then be calculated using Equation 11. The value 100 in the equation converts the decimal percentage to a 100 percent scale. It is important to realize that, when the break in the looped feeder is exactly halfway, the percent power loss equals zero. This means that no additional energy losses are caused by the open-point at that location. This only applies to the halfway point of the loop.

$$\% \text{ Power Loss} = \frac{3\ N_f\ (S_{fault1} + S_{fault2} - S_{norm})}{S_P} \times 100 \qquad \text{[Eq 11]}$$

where:

S_p = Total average peak apparent power per base — VA

Calculate Annual Energy Loss Per Feeder

To calculate the annual energy losses in kWh, the apparent power loss term ($S_{fault1} + S_{fault2} - S_{norm}$) used in Equation 11 must be multiplied by the number of hours in a year and the percent loading factor (Equation 12). Again a 50 percent loading factor is used. The result must be multiplied by three to put it on a per feeder basis, and divided by 1000 to convert to kilowatt-hours:

$$E = \frac{3(8760)(0.5)\,\mathrm{Real}(S_{fault1} + S_{fault2} - S_{norm})}{1000} \qquad \text{[Eq 12]}$$

where:

E = Annual energy loss per feeder — kWh/yr

Example Problem (Chapter 4)

Determine the I^2R and annual kWh energy losses for the loop feeder open-point conditions (Table 6). Assume that (1) the loads are evenly distributed and (2) the break point was initially at the halfway location (0.50). Remember that not all the input current travels the entire length of the feeder and that the current that exits the feeder is precluded from causing an I^2R loss.

Table 6

Looped Feeder System Parameters for Example Problem (Chapter 4)

Parameters	Measure
Effective voltage	12,470/7,200 V
Percent loading	50 percent
Power factor	95 percent
Conductors	2/0 AWG bare copper
Effective current	100 A
Resistance of conductor at 25 °C	0.44+j0.53 Ω/Mile

The annual energy losses shown in Table 7, like those in the example problem in Chapter 3 (p 21), are the total energy losses, including those for a balanced feeder condition. These values are not the losses caused only by feeder circuit load unbalance. However, the annual energy losses shown later in Table 8 for typical Army installations are the losses attributed solely to feeder circuit load imbalances.

Application Considerations

Calculated results of annual energy losses (for typical Army installations) that are caused by feeder circuit load unbalance are presented in Table 8 and Figure 6. Refer to Tables 1 and 2 for applicable Army installation information used to perform calculations. The results listed in Table 8 indicate that the large Army installations were subjected to larger energy losses when feeder loads were unbalanced. The data suggests that the higher power losses for the larger sample bases were due to higher average feeder currents that produced larger voltage drops across the feeder line. The calculations also found that the medium Army installations had the least amount of energy losses. Because all installations had equal feeder lengths, the reason for medium bases having the lowest energy losses can be attributed to their higher feeder voltage and lower feeder current.

Looped feeder systems or separate parallel feeders of different lengths are installed when high reliability is the most important consideration. A looped feeder arrangement (with no open point) maintains a high reliability because it is able to supply all the loads even after sustaining a fault or break in the circuit. A looped feeder circuit also allows a faulty distribution transformer to be isolated and taken off the main feeder line, thereby avoiding a potential break in the loop. The biggest disadvantage of a looped feeder system is its higher initial cost, which is due to the additional components (conductor lines and circuit breakers) required to implement a looped feeder circuit. If reliability is critical, then a looped feeder is considered to be the best type of distribution system to use.

When a looped feeder circuit is incorporated into a distribution system, care must be taken to keep any open-point at the (load) midpoint to avoid additional energy losses. As the calculations support, if the system is allowed to operate with unbalanced feeder loads for a long period of time, then the energy losses could become substantial. To avoid these energy losses for loops with no open-point, all faults and faulty relays must be corrected and/or repaired as soon as possible after detection. As with unbalanced three-phase loads, periodic checks of the looped feeder circuit should be a required preventive maintenance.

Table 7

Results for Example Problem (Chapter 4)

	Open Break on Loop (Percent of Loop Length)					
	50%		60%		80%	
Total Feeder Length (Mile)	I^2Loss (kW)	Energy Loss (kWh/Yr)	I^2R Loss (kW)	Energy Loss (kWh/Hr)	I^2R Loss (kW)	Energy Loss (kWh/Yr)
1	1.65	7,227	1.85	8.094	3.43	15,032
3	4.95	21,681	5.54	24,283	10.30	45,096
5	8.25	36,135	9.24	40,471	17.16	75,161

Table 8

Annual Energy Losses for Unbalanced Feeder Circuit Loads (Per Feeder)

Location Around Loop	Small Base		Medium Base		Large Base	
	Energy Loss (kWh/Yr)	% Power Loss	Energy Loss (kWh/Yr)	% Power Loss	Energy Loss (kWh/Yr)	% Power Loss
0.00	109,430	3.02	135,506	1.51	306,251	3.90
0.05	88,638	2.45	109,760	1.23	248,063	3.16
0.10	70,035	1.94	86,724	0.97	196,000	2.49
0.15	53,621	1.48	66,398	0.74	150,063	1.91
0.20	39,395	1.09	47,782	0.55	110,250	1.40
0.25	27,357	0.76	33,877	0.38	76,563	0.98
0.30	17,509	0.49	21,681	0.24	49,000	0.63
0.35	9,849	0.27	12,196	0.14	27,563	0.35
0.40	4,377	0.12	5,420	0.06	12,250	0.16
0.45	1,094	0.03	1,355	0.02	3,063	0.04
0.50	0	0.00	0	0.00	0	0.00
0.55	1,094	0.03	1,355	0.02	3,063	0.04
0.60	4,377	0.12	5,420	0.06	12,250	0.16
0.65	9,849	0.27	12,196	0.14	27,563	0.35
0.70	17,509	0.49	21,681	0.24	49,000	0.63
0.75	27,357	0.76	33,877	0.38	76,563	0.98
0.80	39,395	1.09	48,782	0.55	110,250	1.40
0.85	53,621	1.48	66,398	0.74	150,063	1.91
0.90	70,035	1.94	86,724	0.97	196,000	2.49
0.95	88,638	2.45	109,760	1.23	248,063	3.16
1.0	109,430	3.02	135,506	1.51	306,251	3.90

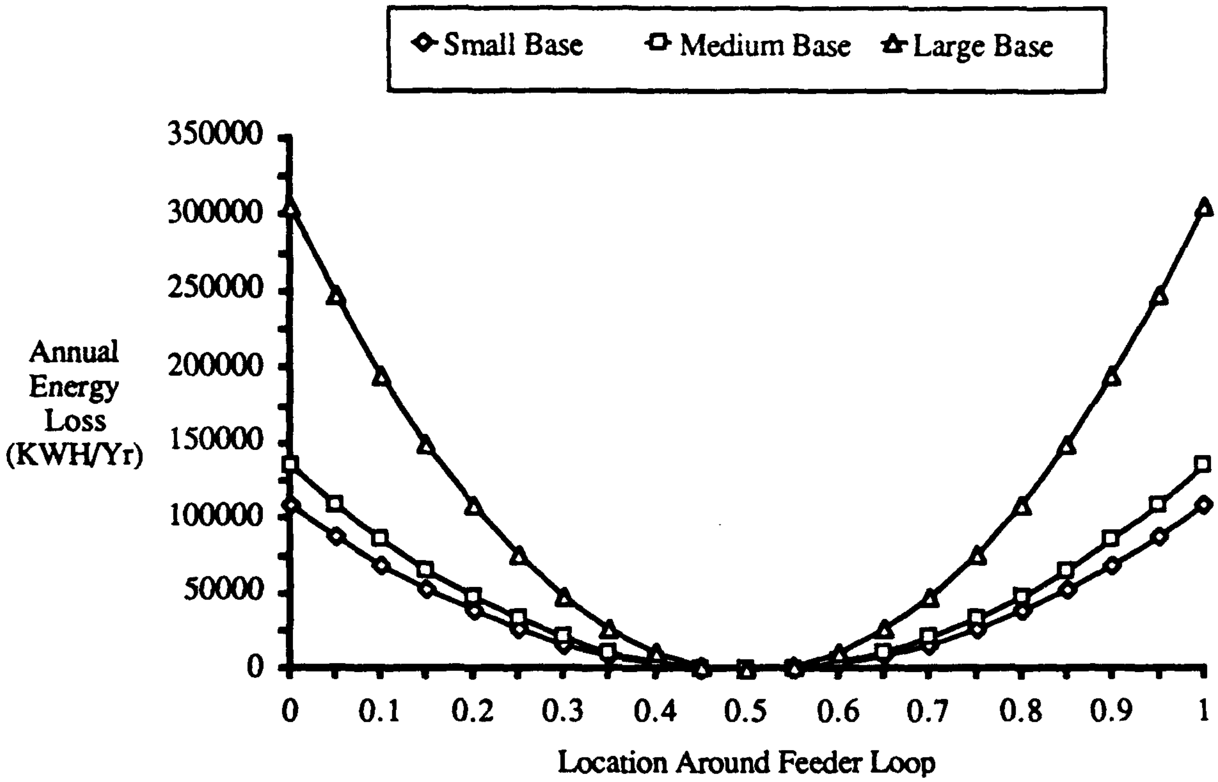


Figure 6. Annual Energy Loss vs. Feeder Loop Location (Per Feeder).

5 POWER FACTOR CORRECTION

Description

An electrical distribution feeder with low power factor must carry extra electrical current (reactive power) in addition to the current (actual power as measured by the kWh meter) required to do work at the load. Operating in a lower power factor condition has several important negative consequences (including reduced system capacity to serve load, additional voltage drop, and possible utility bill penalties). This chapter focuses on the quantification of the sometimes neglected energy losses (I^2R x time) of carrying the extra current associated with a low power factor condition.

Low power factor on an electrical distribution system usually results from serving a load that has a large portion of motors, equipment with transformers such as lighting ballasts or power converters, or other inductive loads. These inductive loads inherently require the distribution system to supply an "energizing" current (for the magnetic fields present in this type of equipment) in addition to the normal current needed to supply useful energy to the load. One way to avoid carrying the energizing current along the distribution system is to place capacitors near the inductive load. Capacitors also require the distribution system to supply a "charging" current, similar to the energizing current for inductive load but opposing in nature, for their operation. However, by selecting a capacitor size such that the capacitive reactive power required by the capacitor matches the inductive reactive power required by the load, the charging/discharging capacitor and the energizing/de-energizing inductive load, swap reactive power back and forth as the system voltage alternates at 60 cycles per second. Therefore, with properly sized capacitors near the inductive load, the distribution system does not have to continuously deliver reactive power (energizing current) along the feeder to the inductive load. Reducing the requirement for reactive power needed from the distribution system is, by definition, an improved power factor condition.

Key Parameters

A number of parameters must be considered when analyzing the effects of power factor on distribution system losses.

Reactive, Actual, and Apparent Power

Figure 7 shows the vector relationship between actual power and reactive power, the sum of which equals the apparent power. The cosine of the angle R equals the ratio of the actual power divided by the apparent power, called the "power factor."

Types of Loads

All devices containing inductance, such as motors, generators, transformers, and other machinery with coils, require reactive currents to produce the magnetic fields needed for their operation. The nature of these currents, as described above, shows them to be the main cause of low power factor. For purely resistive load devices, such as soldering irons and ovens, inductance is not a factor. For resistive devices, the actual and apparent power are equal and the power factor is 100 percent.

Power Factor

Power factor is simply a name given to the ratio of actual power being used in a circuit, expressed in kilowatts, to the total power apparently being drawn from the line, expressed in kilovolt-amperes. Note that unity (a ratio of 1/1) is the maximum value attainable for this ratio. The power factor ratio is of great importance in AC circuits although it has no significance in DC circuits. Army installations, due to their size loads, should operate at or above a 95 percent power factor.

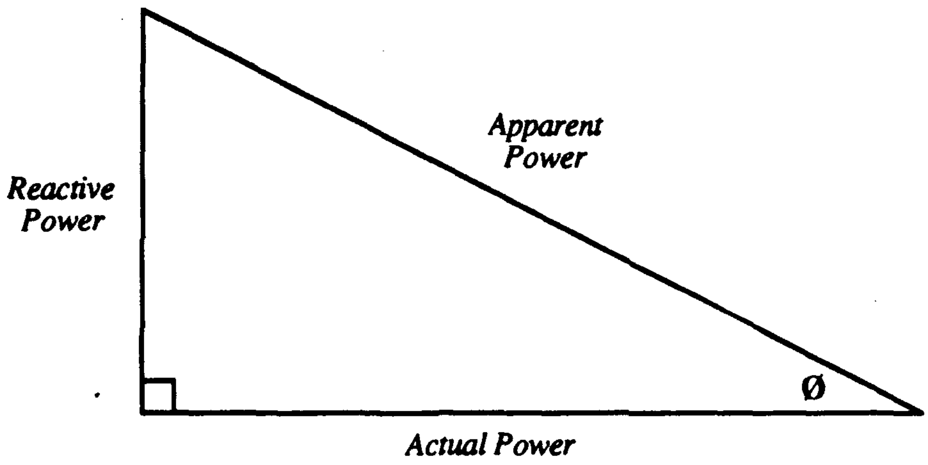


Figure 7. The Power Triangle.

Load Distribution

Load distribution affects power factor correction.

Conductor Size

Because power factor affects the amount of current drawn through a circuit, conductor size is an important factor, especially when conductors are too small to handle the increased loads caused by a low power factor.

Feeder Length

Feeder lines have distribution line losses (I^2R) along their entire length, which causes the voltage to be continually lowered as it travels the feeder line.

Ambient Temperature

Temperature change is not considered for the calculations in this report. A constant ambient temperature of 25 °C is assumed.

Power Factor Penalty

Some utilities charge a penalty for low power factor; however, in this study only energy losses were considered.

Methodology for Determining Energy Savings

To determine estimated energy savings, first the losses of a system that can be reduced must be found. These are losses associated with the extra current that the distribution lines must carry to supply the same real load as when the power factor is at the acceptable level of 95 percent. The additional

current in the distribution lines causes a direct increase in the I^2R losses. This section presents the calculations used to find the energy losses caused by a low factor.

Calculate Peak Effective Phase Current

To calculate energy losses caused by a low power factor, it is first necessary to calculate the peak effective phase current per feeder that would result if the power factor were 95 percent. Equation 13 calculates the peak effective phase current.

$$I_a = \frac{S_p}{3\, N_f\, V_{an}} \qquad \text{[Eq 13]}$$

where:

S_p	=	Total average peak apparent power per base	VA
I_a	=	Peak effective phase current	A
V_{an}	=	Effective line-to-neutral phase voltage	V

Calculate Total Average Peak Apparent Power

Total average peak apparent power was assumed here to be constant in magnitude and phase for the preceding sections. This meant that the power factor was also constant. However, in this section, the power factor functions as a variable. To approximate a variable power factor, the real part of the total average peak apparent power is held constant at a 95 percent power factor while varying the imaginary part.

Calculate Total Percent Power Loss

Once the real current per-feeder per phase is found using Equation 13, it is kept constant. When the power factor is lowered, this causes the reactive power and current to increase. Since the ideal real current is held constant, the reactive current must increase when the power factor decreases. The reason that the real current is held constant is because the actual load on a system is not decreased when the power factor increases. This theory is used to derive Equation 14, which calculates the percent power loss on a 100 percent basis by multiplying the power loss by three times the number of feeders, dividing by two times the total average peak apparent power per base, and then multiplying by 100 to put it on a 100 percent scale.

$$\%\,\text{Power Loss} = \frac{3\, N_f \left| I_a \operatorname{Sin}(\Theta) \right|^2 Z_A}{2\, S_p} \times 100 \qquad \text{[Eq 14]}$$

where:

Q	=	Angle of Lag $\theta = \operatorname{Cos}^{-1}$(power factor)	°
N_f	=	Average number of feeders	-
$Z_{A,B,C}$	=	Line phase impedance $Z_{A,B,C} = Z_t$	Ω

Calculate Annual Energy Loss Per Feeder

To calculate annual energy losses in kWh, the apparent power loss term $((I_a \operatorname{Sin}(\Theta))^2 Z_A)/2$ in Equation 14 must be multiplied by the number of annual hours and the percent loading factor. The loading factor is 50 percent. Multiply it by three to put it on a per-feeder basis, and divide by 1000 to convert to kilowatt-hours:

$$E = \frac{3(8760)(0.5)|I_a \, Sin(\Theta)|^2 \, Real(Z_{A,B,C})}{2(1000)} \qquad [Eq\ 15]$$

where:

E = Annual energy loss per feeder kWh/yr

Example Problem (Chapter 5)

Find the I^2R and annual kWh losses for the feeder conditions (Table 9) and power factors shown in Table 10. Assume that the loads are evenly distributed. Remember that not all the input current travels the entire length of the feeder, and current that exits the feeder is precluded from causing an I^2R loss.

Application Considerations

Annual energy losses for typical Army installations with varying power factors (Figure 8 and Table 11) show that small and large installations had greater energy losses for the same power factor than the medium-sized installations. This can be explained by the higher feeder voltages found at the medium-sized installations in the data base used for this project. These higher feeder voltages caused smaller feeder line currents for the same average peak apparent power. Because this energy loss is an I^2R loss, the lower feeder current produced less distribution line losses for medium-sized installations.

The load ranges of Army applications cause utilities to expect Army installations to have a 95 percent power factor. Installation shoulds strive for a 95 percent power factor minimum. The value of percent power loss for a large installation, which is less than 1 percent per feeder, proves that a 95 percent power factor is effective. This small loss is seen as the cost of delivering power to the customer.

To summarize, the effects of a low power factor are twofold: (1) a low power factor causes increased I^2R losses in the distribution lines, (2) an Army installation must be aware of the possible monetary penalty for a low power factor that may be charged by the utility (if applicable). Although the power factor penalty is not considered in this report, it still may have a great impact on monthly utility charges. Therefore, an Army installation should understand the implications of the power factor clauses that may or may not apply to them.

The most practical and economical power factor correction device is the capacitor. Utilities routinely install capacitors at power stations and on distribution feeders where an elaborate and expensive synchronous motor installation is not justified.

Table 9

Power Systems Parameters for Example Problem (Chapter 5)

Parameters	Measure
Effective voltage	12,470/7,200 V
Conductors	2/0 AWG bare copper
Percent loading	50 percent
Effective current	100 A
Resistance of conductor at 25 °C	0.44+j0.53 Ω/Mile

Table 10

Results for Example Problem (Chapter 5)

Total Feeder Length (Mile)	Power Factor: 90% I²R Loss (kW)	90% Energy Loss (kWh/Yr)	80% I²R Loss (kW)	80% Energy Loss kWh/Hr	70% I²R Loss (kW)	70% Energy Loss (kWh/Yr)
1	8.15	35,689	10.31	45,167	13.47	58,996
3	24.44	107,067	30.94	135,506	40.41	176,988
5	40.74	178,445	51.56	225,844	67.35	294,980

Capacitors improve power factor because the effects of capacitance are exactly opposite those of inductance. Adding capacitors to an inductive circuit essentially cancels out the effect of the circuit inductance, reducing the net amount of reactive power, and consequently increasing the power factor.

Capacitors offer several advantages over other types of power-factor correction devices; they: (1) have a substantially lower cost, (2) are easily moved within an electrical distribution network as required, (3) can be installed economically in a decentralized manner, (4) require minimal maintenance, and (5) have a correction capability (of a capacitor bank) easily sized to meet the reactive load.

If capacitors are going to be installed to improve the power factor, care should be taken to match the capacitive reactance with the inductive reactance of the distribution system. Too much capacitance in the system has the same adverse effect as too much inductance. The difference is that capacitance causes a leading power factor, whereas the inductance produces a lagging power factor.

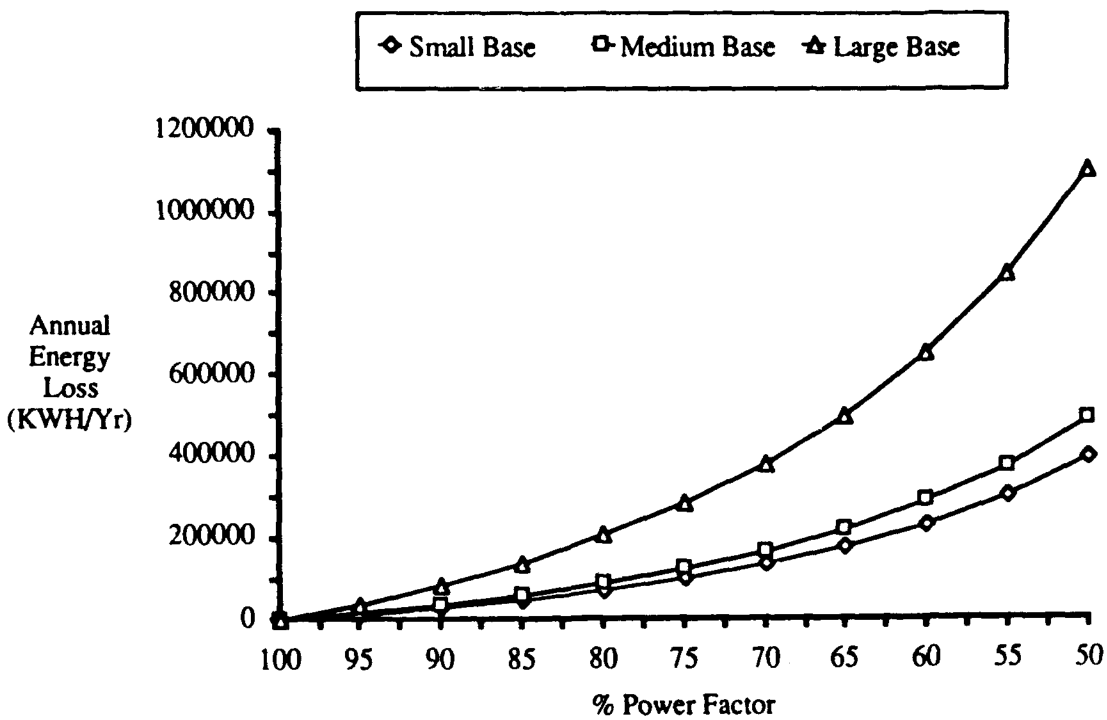


Figure 8. Annual Energy Loss vs. Power Factor (Per Feeder).

Table 11

Annual Energy Loss for Various Power Factors (Per Feeder)

Percent Power Factor	Small Base % Power Loss	Small Base Energy Loss (kWh/Yr)	Medium Base % Power Loss	Medium Base Energy Loss (kWh/Yr)	Large Base % Power Loss	Large Base Energy Loss (kWh/Yr)
100	0.00	0	0.00	0	0.00	0
95	0.39	14,297	0.20	17,704	0.50	39,748
90	0.81	31,043	0.41	38,440	1.03	86,302
85	1.26	50,830	0.63	62,943	1.59	141,312
80	1.73	74,442	0.87	92,181	2.20	206,955
75	2.24	102,932	1.12	127,460	2.85	286,160
70	2.80	137,743	1.40	170,567	3.56	382,937
65	3.42	180,893	1.71	223,998	4.34	502,897
60	4.10	235,274	2.05	291,338	5.21	654,080
55	4.88	305,151	2.44	377,867	6.19	848,345
50	5.77	397,025	2.88	491,633	7.32	1,103,761

6 OPTIMAL TRANSFORMER SIZING

Description

This chapter discusses how sizing transformers affects energy losses. While balancing other concerns (such as providing sufficient capacity without damaging the transformer while minimizing initial equipment costs) is a primary consideration, it is also desirable to be aware of transformer energy losses, which could be an important factor when deciding whether to change-out an in-place, oversized transformer (which could occur for a number of reasons). Optimally sized transformers minimize distribution system energy losses. An optimally sized transformer is defined as a transformer that has a capacity (kVA rating) closely matching the load requirement. A transformer should not be severely undersized or oversized; however, the main concern should be undersized transformers. Using an undersized transformer causes overloading, reduces efficiency, and is more likely to cause overheating.

Based on transformer capacity, a larger transformer at full load generally has a lower percentage of total losses compared to a smaller transformer. However, the actual losses may be higher on the transformer with a larger capacity despite the lower percentage of losses (i.e., higher efficiency).

Key Parameters

Transformer losses involve a number of parameters, including no-load (core) loss and load (copper) loss.

No-Load and Load Losses

To assess transformer losses, consider the case of an ideal transformer. In an ideal transformer, with no energy losses, the following conditions would apply:

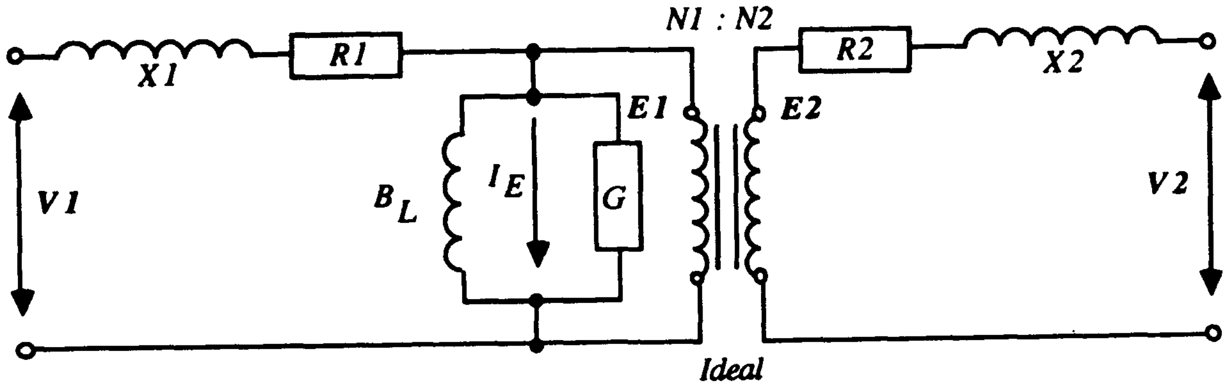
1. Infinite permeability
2. No winding resistance
3. No losses in the iron core due to cyclic changing of flux polarity
4. Perfect flux linkage.

However, in the case of a practical transformer, none of these conditions exist—energy losses are the rule.

In a nonideal transformer, the first condition—finite permeability—implies that, as the load increases and the core becomes more saturated with flux, more of the magnetic flux produced by the coil leaks to a path outside of the core. This flux leakage, termed "leakage reactance" and shown as X1 and X2 in Figure 9, results in energy losses.

The second condition—winding resistance—is the result of the commonly understood phenomena that all electrical conductors have resistance. As the load on the transformer and the corresponding current through the coil increases, (I^2R) losses increase. Winding resistances are shown as R1 and R2 in Figure 9. Note that, for both of these conditions, losses vary as a function of the load. Hence, these losses are called load (or coil) losses.

The third condition—losses in the core due to cyclic changing of flux polarity—result from using iron in an alternating circuit. When subjected to a magnetic field, iron is irreversibly altered and will retain residual magnetism without the continued presence of a magnetic field. This residual magnetism must be overcome with each change in polarity (at 60 Hertz). The result is a loss called hysterisis loss. In Figure 9, hysterisis loss is primarily associated with the B_L—Inductive Susceptance parameter.



$X1$, $X2$	*Leakage Reactance*	Ω
$R1$, $R2$	*Winding Resistance*	Ω
G	*Conductance*	$1/\Omega$
I_E	*Magnetizing Current*	A
B_L	*Inductive Susceptance*	$1/\Omega$

Figure 9. Practical Transformer Equivalent Circuit.

The fourth condition—imperfect flux linkage—occurs in a nonideal transformer. One consequence of this condition, combined with the presence of time-varying magnetic fields, is that voltages will be induced around various closed paths in the solid core. These induced voltages will give rise to currents, known as Eddy currents. Eddy currents result in heating of the core and an I^2R type of loss in it. In Figure 9, eddy-current losses are primarily associated with parameter G—Conductance. Note that, for conditions 3 and 4, losses result whenever the transformer is energized; even when no load is being served. Thus, these losses are called no-load (or core) losses.

The no-load percent and load loss percent for a transformer can be obtained from the manufacturer. This information is required to estimate transformer losses, as will be discussed next.

Temperature

The operating temperature of the transformer is another variable that affects the quantity of no-load and load losses. Typically, no-load losses are lower at higher temperatures and load losses increase as the temperature rises. Total losses (sum of no-load and load losses) will also be greater at higher temperatures.

Methodology for Determining Energy Savings

Even when a transformer is optimally sized, it still has energy losses. Because the loading on a transformer fluctuates hourly, calculating the energy losses requires the use of some standardized method. The method used in this report (Figure 10) is taken from ASHRAE/IES Standard 90.1, *Energy Conservation* (American Society of Heating, Refrigeration and Air Conditioning Engineers [ASHRAE], 1989). This method only estimates the total losses (no-load and load losses) for a transformer. It does not address the additional losses that result from an improperly sized transformer.

1. *No-load transformer loss (%) manufacturers rating = _________ %*

2. *No-load (%) loss x transformer full-load KVA = _________ KW*

3. *Annual no-load losses: 8,760 x no-load KW (#2 above) = _________ KWH*

4. *Annual hours of transformer operation from 10% to 50% load = _________ Hrs*

5. *Use 10% of transformer full-load coil losses x #4 above = _________ KWH*

6. *Annual hours of transformer operation from 50% to 80% load = _________ Hrs*

7. *Use 40% of transformer full-load coil losses x #6 above = _________ KWH*

8. *Annual hours of transformer operation from 80% to 100% load = _________ Hrs*

9. *Use 80% of transformer full-load coil losses x #8 above = _________ KWH*

10. *Total Energy Loss KWH of #3, #5, #7, #9 = _________ KWH*

Figure 10. ASHRAE Method for Calculating Transformer Total Energy Losses.

The steps to the ASHRAE method (Figure 10) are as follows: First, obtain the manufacturer no-load (percent) specification (#1) and also the load loss (percent). Multiply the no-load percent by the transformer full-load kVA rating (#2). Then calculate the annual no-load losses by multiplying the no-load loss (#2) by 8760 hours (#3). Now, estimate the number of hours a year the transformer operates at low loads (10 to 50 percent load) (#4). Multiply the low-load hours by 10 percent of the transformer full-load coil loss to obtain the load loss at low loads (#5). The full-load coil loss is calculated by multiplying the transformer capacity (kVA) by the manufacturer's load loss (percent) specification. Now estimate the annual hours of operation (#6) at medium loads (50 to 80 percent load) and multiply by 40 percent of the full-load coil loss to find the load loss for medium loads (#7). For load losses at full-load (80 to 100 percent load), multiply the estimated full-load hours (#8) by 80 percent of the full-load coil loss (#9). The annual total loss in kWh (#10) is equal to the sum of the losses calculated in steps #3 (no-load loss), #5 (load loss at low loads), #7 (load loss at medium loads), and #9 (load loss at full loads) of the procedure.

As stated above, the ASHRAE method does not address additional losses resulting from an undersized or oversized transformer. To compare an oversized/undersized transformer to an optimally sized one is a difficult task. To estimate the additional losses due to mis-sizing requires that transformers be compared on a case-by-case basis. There must be a known load. Then the total losses can be calculated for different transformers using the ASHRAE method. (The ASHRAE method cannot be used to estimate losses for an undersized transformer). The optimal transformer should have a capacity close to the load requirement and should have the least losses. The difference between the losses of the optimal transformer and a mis-sized transformer is the "additional loss."

If an undersized 75kVA transformer handles a 100kVA load, the energy losses calculated using the ASHRAE method would be less than those of a 100kVA transformer (optimal transformer) supplying the 100kVA load. The reason the method cannot be used for undersized transformers is that the percentages of 0.1 (low-loads), 0.4 (medium-loads), and 0.8 (full-loads) that estimate the load losses tend to exaggerate the loss estimate toward a lower value. A better mix of load loss percentages must to be used for overload (undersized) conditions to arrive at a realistic estimate.

This report uses the ASHRAE method to analyze losses for oversized transformers. In the case of undersized transformers, the report uses a modified version of the ASHRAE method. The modified method uses load loss percentages of 0.25 (low-load), 0.7 (medium-load), and 1.3 (full-load).

To analyze different transformers, the first thing that was done was to choose some typical distribution transformer sizes used by Army installations. The total losses were calculated for each size using the ASHRAE method. These losses are considered the baseline or optimal value losses for comparison to mis-sized transformers. The next step uses both the ASHRAE method (oversized) and modified method (undersized) to calculate the losses for mis-sized cases. The report assumes an oversized transformer to be the next size up (Tables 12 and 13). Similarly, an undersized one is assumed to be the next size smaller. There may be transformer sizes which are between sizes, but this study used standard sizes for comparison. The difference in losses between the baseline transformer and the over-sized/undersized transformer is the additional loss that results from not using an optimally sized transformer.

Table 12 lists manufacturer averages for no-load percent and load loss percent that are needed for use with the ASHRAE method. As stated previously, temperature will affect these values. This report uses the values listed at 115 °C for calculations. The values in Table 12 were obtained from several studies and are fairly standard across the spectrum of manufacturers.

Operational hours are also required to perform the ASHRAE method. Based on several distribution system studies, it was found that a typical distribution transformer operates on the average about 7 hours a day at low-load, nearly 10 hours at medium-load, and 7 hours at full-load. Converting these to annual values results in 2555, 3650, and 2555 hours for the three load conditions respectively. These values are used to estimate the baseline losses for each transformer size (Table 13).

In the case of oversizing, it was assumed that a transformer operates annually at 4380 hours for both low-load and medium-load conditions. Based on ratio analysis, it was also assumed that undersized transformers do not reach the full-load range; therefore zero hours are used in the calculations. Using the same idea for undersized transformers, 1825 hours (low load), 2555 hours (medium load), and 4380 hours (full load) were assumed as the operating times.

Example Problem (Chapter 6)

Calculate the no-load losses, load losses, and total losses in kW for a 50, 75, and 100kVA transformer at 50 percent, 75 percent, and 100 percent loading conditions (Table 14). Also find the annual energy loss (kWh) for the 50 percent load condition. For each loading condition, assume the transformer operates 8760 hours/yr in that range, and also assume an operating temperature of 80 °C.

Application Considerations

Using the procedure outlined in Methodology for Determining Energy Savings (above), the annual energy losses (per transformer) were calculated for different transformer sizes (using the ASHRAE

Table 12

Manufacturer No-Load Percentage and Load Loss Percentage

Transformer Rating (kVA)	% No-Load & Load Losses Different Size Transformers Ranges								
	Core Loss (%)			Load Loss (%)			Total Loss (%)		
	150°C	115°C	80°C	150°C	115°C	80°C	150°C	115°C	80°C
30-225	0.50	0.75	0.80	3.00	1.90	1.70	3.50	2.60	2.40
300-500	0.40	0.50	0.50	2.20	1.80	1.40	2.65	2.30	2.12
700-1000	0.30	0.34	0.34	2.10	1.80	1.40	2.50	1.90	1.74

Table 13

Results for Example Problem (Chapter 6)

Transformer Size (kVA)	100% Load Core Loss (kW)	100% Load Load Loss (kW)	100% Load Total Loss (kW)	75% Load Core Loss (kW)	75% Load Load Loss (kW)	75% Load Total Loss (kW)	50% Load Core Loss (kW)	50% Load Load Loss (kW)	50% Load Total Loss (kW)	Energy kWh/yr
50	0.40	0.68	1.08	0.40	0.34	0.74	0.40	0.09	0.49	4,292
75	0.60	1.02	1.62	0.60	0.51	1.11	0.60	0.13	0.73	6,395
100	0.80	1.36	2.16	0.80	0.68	1.48	0.80	0.17	0.97	8,497

Table 14

Annual Energy Losses for Different Size Transformers (Per Transformer)

Transformer Capacity (kVA)	No-Load Losses (kWh)	Low-Load Losses (10-50% (kWh)	Medium-Load Losses (50-80%) (kWh)	Full-Load Losses (80-100%) (kWh)	Total Energy Losses (kWh)
5	329	24	139	194	686
10	657	49	277	388	1,371
15	986	73	416	582	2,057
25	1,643	121	694	971	3,429
37.5	2,464	182	1,040	1,456	5,142
50	3,285	243	1,387	1,942	6,857
75	4,928	364	2,081	2,913	10,286
100	6,570	485	2,774	3,884	13,713
167	10,972	811	4,633	6,486	22,902
250	10,950	1,150	6,570	9,198	27,868
333	14,585	1,531	8,751	12,252	37,119
500	21,900	2,300	13,140	18,396	55,736

method). The results are listed in Table 13. These values are the baseline or associated losses for transformers considered to be optimally sized to meet the load. The additional losses caused by improperly sized transformers (both undersized and oversized) are shown in Table 15.

The results indicate that energy losses for mis-sized transformers calculated for this example varied from –7 to +30 percent for oversized transformers. For most transformers sizes, oversizing the transformer

caused greater losses. However, several sizes did not follow this trend; it is not true to say that oversizing always brings additional losses. The kWh quantity associated with oversizing varied from several hundred to more than 4000. At $0.05 per kWh, this implies annual costs for losses from $10 to $200. At $10 annual costs, losses will not be a primary consideration in transformer selection. However, $200 per year in losses over the life of a transformer could be a very significant factor in an economic evaluation.

The calculated losses for undersized transformers of various sizes varied even more than losses for oversized transformers. Again, both positive and negative values were observed. However, energy losses are likely to be a secondary consideration when evaluating an undersized transformer. Equipment life and service reliability factors will likely overshadow the importance of energy losses for undersized transformers.

It should be emphasized that these losses were calculated by the ASHRAE method, which uses an assumed load. Results could be different for loads that differ from the assumed load. Also, these calculations used typical transformer losses from an average of various manufacturer's transformers. Individual transformers could vary and, therefore, have different results.

The amount of transformer losses on an Army installation will be determined by the number and size of transformers on the installation, not merely by the size of the installation. Due to the high cost of transformers, the prime time to consider the cost of energy losses is when transformers are being selected for replacement or new construction. It is unlikely that energy losses would warrant replacement of an existing operational transformer.

Table 15

Additional Energy Losses for Mis-Sized Transformers (Per Transformer)

Optimal Transformer Load (kVA)	Total Loss (Baseline) (kWh)	Additional Losses Oversized (kWh)	% Increase Oversized)	Additional Losses Undersized (kWh)	% Increase Undersized
5	686	387	56.4	—	—
10	1,371	239	17.4	-288	-20.9
15	2,057	626	30.4	108	5.3
25	3,429	595	17.4	-180	-5.2
37.5	5,142	224	4.4	272	5.3
50	6,857	1,192	17.4	1,263	18.4
75	10,286	445	4.3	541	5.3
100	13,713	4,208	30.7	2,528	18.4
167	22,902	-1,549	-6.8	-1,248	-5.4
250	27,868	-156	-0.5	9,043	32.4
333	37,119	4,491	12.1	13,223	35.6
500	55,736	—	—	6,434	11.5

7 CONSERVATION VOLTAGE REDUCTION

Description

This chapter discusses the use of conservation voltage reduction (CVR) as a way to reduce distribution system energy losses (and energy consumption of loads). Conservation voltage reduction is a way of continuously supplying the minimum acceptable voltage to the customer (at the lowest voltage point in the system) by regulating the distribution feeder voltage. By reducing supply voltage to a minimum, resistive loads use proportionally less energy.

For example, if the voltage supplied to a customer operating 100 percent resistive type loads is lowered by 2 percent (from 120V to 117.6V), the energy consumed by customer would theoretically be 4 percent less (Power = V^2/Z). Note that on actual systems that are not 100 percent resistive, due primarily to motor loads, lowering the voltage by 2 percent would yield less than a 4 percent energy reduction. This occurs because, when the voltage to a motor is lowered, the motor draws more current, which not only prevents energy savings, but can also increase I^2R losses (because of the higher current). Care must also be taken to ensure that the voltage does not drop beyond tolerable levels to avoid high currents that cause overheating and damage in motors.

The difficulty in executing CVR is properly regulating the feeder voltage to maintain the desired voltage at a distant customer's point of use. Voltage drop along the feeders varies as the load on the feeder varies. To compensate for this voltage drop variation, a control algorithm can be developed from engineering calculations by building a control feedback electronic circuit that models feeder impedance, or, conceivably, by using end-of-line voltage measurements.

This chapter will provide a sample calculation that gives a "ballpark" indication of the possible energy savings for typical distribution feeder. These sample calculations are based on a 100 percent resistive type load. This means that realistic expectations for energy savings will probably be somewhat less.

Key Parameters

The parameters identified below are important factors when analyzing conservation voltage reduction.

Voltage Regulation

The primary concern when considering conservation voltage reduction is voltage regulation. Numerous regulatory commissions allow variations of about ±5 percent from nominal voltage for lighting service; for a nominal 120V, the favorable operating range is 114 to 126V. The Army design criteria suggests a stricter voltage tolerance of ±2 percent, making the voltage range 117.6 to 122.4V. This tighter tolerance decreases the amount of possible voltage reduction. For example, if a nominal voltage of 120V is reduced by 2V, only 0.4V of reduction capability remains. This means that the end of feeder voltage must not drop below 117.6V (Figure 11). Remaining within the acceptable voltage range helps protect equipment (air conditioners, refrigerators, induction motors, and generators) from being damaged.

Load Distribution

In reality, feeder load locations determine what voltage must be supplied to meet that particular load requirement. However, to simplify the calculations, feeder loads are assumed to be evenly distributed.

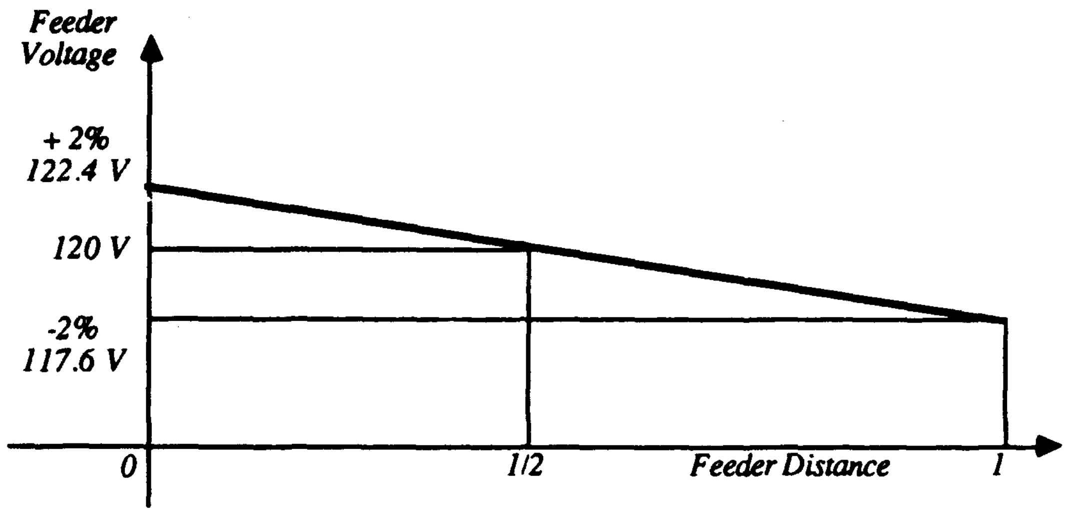


Figure 11. Feeder Voltage vs. Feeder Balance (at Full Load Current).

Apparent and Actual Power

Definitions were discussed in earlier sections.

Conductor Size

Conductor impedance (Z) affects the amount of voltage dissipated in the distribution line (V = IZ). The size of this voltage drop determines whether the system has a good or poor voltage regulation. Obviously, the lower the voltage drop, the better the voltage regulation.

Feeder Length

Feeder lines have distribution line (I^2R) losses along their entire length; therefore the voltage continually is being reduced as it travels the feeder line.

Ambient Temperature

A constant ambient temperature of 25 °C is assumed.

Methodology for Determining Energy Savings

This section addresses conservation voltage reduction on a quantitative basis. The pertinent energy loss equations are discussed below.

Calculate Total Load and Line Impedance

First, total load and line phase impedances are calculated assuming a balanced state. To do this, the effective line-to-neutral voltage squared is multiplied by three times the number of feeders and divided by the total average peak apparent power (volt-amperes). (The factor of three accounts for the three phases.) The result is Equation 16. The subscripts indicate that Equation 16 applies for all phases.

$$Z^{*}_{Aa,Bb,Cc} = \frac{3\,N_f\,|V_{abcn}|^2}{S_p} \qquad \text{[Eq 16]}$$

where:

$Z_{Aa,Bb,Cc}$	=	Total load and line phase impedance	Ω
N_f	=	Average number of feeders	Ω
S_p	=	Total average peak apparent power per base	VA
V_{abcn}	=	Effective line-to-neutral phase voltage	V

Calculate Total Percent Power Loss

To calculate the power loss in volt-amperes, V_r (reduced voltage) squared is subtracted from the nominal voltage V_{abcn} squared. The reduced voltage is obtained by assuming a certain percentage of the nominal voltage. For example, if the nominal voltage is 120V, and a 5 percent reduction is used, then the reduced voltage V_r would equal (120)(0.95) or 114V. To find the percent power loss (1 percent scale), the difference in the two voltages squared must be multiplied by three times the number of feeders and divided by the total load and line impedance and peak apparent power per base (Equation 17).

$$\% \text{ Power Loss} = \frac{3\,N_f \left| V_{abcn}^2 - V_r^2 \right|}{\left| S_p\, Z_{Aa,Bb,Cc}^* \right|} \times 100 \qquad \text{[Eq 17]}$$

Calculate Total Annual Energy Loss Per Feeder

The annual energy loss is calculated by multiplying the power loss term $[(V_{abcn})^2 - (V_r)^2]/Z_{Aa,Bb,Cc}$ in Equation 17 by the number of hours in a year; the loading factor, which is assumed to be 50 percent; and three (which accounts for the three phases). The power loss term is also divided by 1000 to convert to kilowatt-hours (Equation 18). An important thing to consider here is that when the percent power and

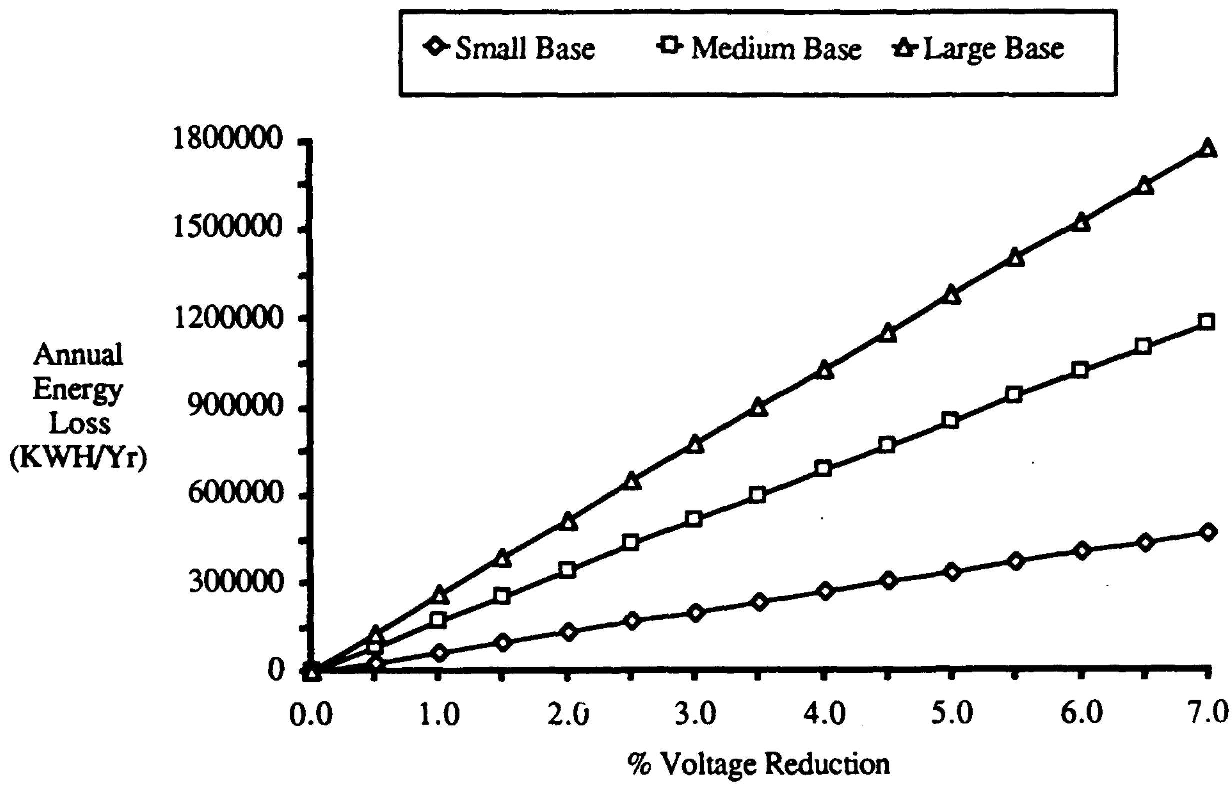


Figure 12. Annual Energy Loss vs. Percent Feeder Voltage Reduction (Per Feeder).

the annual energy losses are calculated, the feeder length is not divided by two to compensate for the evenly distributed loads.

$$E = \text{Real}\left|\frac{3(8760)(0.5)\left|V_{abcn}^2 - V_r^2\right|}{(1000)Z_{Aa,Bb,Cc}^{*}}\right| \qquad \text{[Eq 18]}$$

where:

E = Annual energy loss per feeder — kWh/yr

Example Problem (Chapter 7)

CVR will be implemented on a feeder that has the parameters given in Table 16. The end of line voltage V_{eol} will be adjusted so that it is exactly 113V. There is a 3 percent voltage drop along the secondary. Calculations will be made for different loading conditions and feeder lengths. Total annual energy losses will be calculated for V_{eol} equal to 113V and 120V and then compared. The difference equals the annual energy that could be saved if CVR was implemented. The amount of annual energy loss is quite large because the feeder length is not divided by two in the calculations.

Application Considerations

The CVR methodology discussed above was used to calculate estimated annual energy losses for typical Army installations. Those results are shown in Table 18 and Figure 12. From Table 17, a medium sized Army Base could expect approximately 433,000 kWh per year (per feeder) of energy savings for a 2.5 percent voltage reduction. At $0.05 per kWh, this suggests energy savings of $21,000 per year (per feeder). However, as previously stated, the assumption of 100 percent resistive type load causes energy savings to be overestimated. In Table 17, a 1 percent reduction in voltage creates approximately 2 percent reduction in power. One actual field study of CVR suggests that, instead of a 2 to 1 ratio, a more realistic ratio (percentV/ percentE) is 1.63 (Kennedy and Fletcher, "Conservation Voltage Reduction (CVR) at Snohomish County PUD," *IEEE Transactions on Power Systems*, Vol 6, No. 3 [August 1991], pp 986-998). Using the 1.63 ratio would indicate that the $21,000 energy savings suggested (above) might be adjusted to a more realistic $17,000 per year (per feeder).

While it is apparent that CVR can save significant quantities of energy, many utility engineers are wary of giving up the margin of safety in the voltage tolerance by intentionally operating the distribution system at some minimum acceptable voltage. To implement CVR, feeder loads and the associated voltage

Table 16

Power System Parameters for Example Problem (Chapter 7)

Parameters	Measure
Effective voltage	12,470/7,200 V
Power factor	95 percent
Conductors	2/0 AWG Bare Copper
Percent loading	50 percent
Effective current (100 percent)	100 A
Resistance of conductor at 25 °C	0.44+j0.53 Ω/Mile

Table 17

Results for Example Problem (Chapter 7)

Total Feeder Length (Mile)	100A Load V_s (V)	V_{out} (V)	Pow (kW)	75A Load V_s (V)	V_{out} (V)	Pow (kW)	50A Load V_s (V)	V_{out} (V)	Pow (kW)	Energy kWh/yr
2	7,504	120	2,251	7,482	120	1,683	7,460	120	1,119	4,901,220
2	7,071	113	2,121	7,049	113	1,586	7,027	113	1,054	4,617,002
4	7,592	120	2,278	7,548	120	1,698	7,504	120	1,126	4,930,128
4	7,159	113	2,148	7,115	113	1,601	7,071	113	1,061	4,645,910
6	7,680	120	2,304	7,614	120	1,713	7,548	120	1,132	4,959,036
6	7,247	113	2,174	7,181	113	1,616	7,115	113	1,067	4,674,818

Table 18

Annual Energy Losses for Conservation Voltage Reduction (Per Feeder)

% Voltage Reduction	Small Base % Power Loss	Small Base Energy Loss (kWh/Yr)	Medium Base % Power Loss	Medium Base Energy Loss (kWh/Yr)	Large Base % Power Loss	Large Base Energy Loss (kWh/Yr)
0.0	0.00	0	0.00	0	0.00	0
0.5	1.00	34,960	1.00	87,394	1.00	131,104
1.0	1.99	69,746	1.99	174,351	1.99	261,550
1.5	2.98	104,355	2.98	260,869	2.98	391,340
2.0	3.96	138,790	3.96	346,949	3.96	520,472
2.5	4.94	173,050	4.94	432,592	4.94	648,947
3.0	5.91	207,134	5.91	517,796	5.91	776,765
3.5	6.88	241,043	6.88	602,562	6.88	903,925
4.0	7.84	274,776	7.84	686,890	7.84	1,030,429
4.5	8.80	308,335	8.80	770,780	8.80	1,156,275
5.0	9.75	341,718	9.75	854,232	9.75	1,281,464
5.5	10.70	374,926	10.70	937,245	10.70	1,405,996
6.0	11.64	407,959	11.64	1,019,821	11.64	1,529,871
6.5	12.58	440,816	12.58	1,101,959	12.58	1,653,089
7.0	13.51	473,498	13.51	1,183,658	13.51	1,775,650

drops must be accurately compensated for. This implies careful and accurate engineering calculations and/or field measurements. Failure to properly control system voltage could result in overheating of motors, which affects equipment [illegible].

In many cases, the simplest place to implement CVR control of feeder voltage is at a substation transformer, typically equipped with tap-changing capability to control voltage. However, such substation transformers may serve several feeders, therefore, not permitting voltage control for individual feeders. Without individual control of feeders, energy savings from CVR will not be maximized.

Implementation of CVR also means that future additional loads and extensions of feeders will need to be carefully considered to adjust the feeder voltage control algorithm.

8 CONDUCTOR SIZING

Description

This chapter evaluates the reduction in energy losses that can be expected from using a conductor size larger than the typically selected size. Typically, conductor selection attempts to select a conductor that can carry the load current without exceeding a specific voltage drop and a safe operating temperature. The limiting design factor for overhead conductors is sometimes voltage drop; for underground cables, it may be either voltage drop or current carrying capacity.

The size of a conductor affects the characteristics of the wire, including impedance. Impedance varies inversely with wire size; therefore larger wire sizes will have less impedance or resistance to the flow of current. A lower impedance also produces smaller voltage drops across the wire, which results in reduced power dissipation (energy losses) in the feeder line.

Key Parameters

The key elements involved in comparing conductor sizes are discussed below.

Resistance and Inductive Reactance

Figure 13 shows the equivalent circuit model for a short length distribution line. The capacitive reactance has been omitted from the circuit model because capacitance has minimal effects on the normal operation of a distribution line until the voltage reaches about 132,000V and the length of the line exceeds 100 miles. From Table 1, it is evident that the effective line-to-line voltages at Army installations do not exceed this limit. Therefore, the two major concerns with regard to conductor sizing, will be resistance and inductive reactance. Combined, these parameters equal impedance. Standard tables, available in any electrical engineering handbook (e.g., Charles Belove, ed., *Handbook of Modern Electronics and Electrical Engineering* [Wiley-Interscience, 1986]) list values for resistance and reactance on a per mile, per phase, and per unit-foot basis.

Load Distribution

Load spacing is a factor that must be considered when sizing a conductor to meet a load requirement. In this report, feeder loads are assumed to be evenly distributed.

Apparent and Actual Power

Definitions were presented in Chapter 3, **Key Parameters** (p 16).

Conductor Impedance

Conductor impedance directly affects the amount of voltage drop along the conductor line ($V = IZ$).

Feeder Length

Feeder lines produce line (I^2R) losses as the current travels the length of the line. Longer conductor lines will have more losses (I^2R).

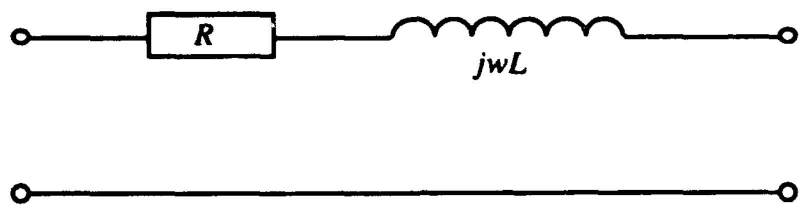


Figure 13. Short Distribution Line Model With Neutral Return.

Ambient Temperature

An ambient temperature of 25 °C is assumed.

Power Factor

A power factor of 95 percent is assumed.

Methodology for Determining Energy Savings

This section presents the procedure used to calculate energy losses that result from different sized conductors.

Calculate Peak Effective Current Per Feeder Per Phase

To calculate the peak effective current per feeder per phase, the effective line-to-neutral voltage is divided by the total load and line phase impedance Equation 19.

$$I_a = \frac{V_{an}}{Z_{A_a}} \qquad \text{[Eq 19]}$$

where:

I_a	=	Peak effective phase current	A
V_{an}	=	Effective line-to-neutral phase voltage	V
Z_{A_a}	=	Total load and line phase impedance $Z_{A_a} = Zt$	Ω

Determine Line Phase Impedance

To calculate the line impedance of the distribution (conductor) line (Z_A), the line impedance per mile (Z_l) is multiplied by the average feeder length.

Calculate Distribution Line Apparent Peak Power Loss

Equation 20 shows that the peak apparent power loss for a given distribution line is equal to the line impedance times the square of the absolute value of the effective current carried by the distribution line. This equation shows the direct relationship between the conductor's size and the quantity of energy losses.

$$S_l = |I_a|^2 Z_A \qquad \text{[Eq 20]}$$

where:

Z_A	=	Line phase impedance $Z_A = Z_t = Z_l L_f$	Ω
S_l	=	Peak apparent power loss per phase	VA

Calculate Percent Power Loss

To calculate the percent power loss (Equation 21), the first step is to adjust the line-phase impedance. This is done by taking the difference between the impedance of the conductor under investigation, Z_{Cond}, and the line impedance, Z_A. The line impedance is estimated by first calculating the peak effective phase current. Once the peak effective phase current is known, it is possible to select a conductor from standard tables that can safely handle the current. The conductor's impedance per mile value can also be found in this table. The impedance must be divided by two to approximate the average distance current travels in the feeder. Multiplying this adjusted impedance by the effective phase current squared gives the power loss for one phase of the distribution line. Next, multiply this power loss by three times the number of feeders and divide by the total average peak apparent power for the base. This is the fractional percent power loss for the conductor (per feeder). Multiplying it by 100 converts it to a 100 percent scale.

$$\%\,\text{Power Loss} = \frac{3\,N_f\,|I_a|^2 (Z_A - Z_{Cond})}{2\,S_p} \times 100 \qquad \text{[Eq 21]}$$

where:

S_p	=	Total average peak apparent power per base	VA
N_f	=	Average number of feeders	-
Z_{Cond}	=	Test conductor phase impedance	Ω

Calculate Total Annual Energy Loss Per Feeder

The annual energy loss (kWh) is calculated by multiplying the power loss term $I_a 2\ (Z_A\ .\ Z_{Cond})/2$ in Equation 21 by the number of hours in a year and the assumed loading factor of 50 percent. The power loss term must then be divided by 1000 to obtain the energy losses in kilowatt-hours:

$$E = \frac{3(8760)(0.5)|I_a|^2 (Z_A - Z_{Cond})}{2(1000)} \qquad \text{[Eq 22]}$$

where:

E	=	Annual energy loss per feeder	kWh/yr

Example Problem (Chapter 8)

A new three-phase distribution line is to be installed. Table 19 lists the power system parameters. Assuming evenly distributed loads, calculate the I^2R and the annual kWh loss for the three different size conductors given in Table 20. Assume a 100A load for all cases. Results for the problem are given in Table 20.

Application Considerations

From Table 18 for a 3-mile feeder length, the difference in annual energy loss between a #1/0 conductor and a #2/0 conductor is approximately 24,000 kWh. At $0.05 per kWh, this is $1200 per year in energy costs. For the loads assumed for this example, the estimated $1200 annual energy savings would probably provide a 2 to 3-year payback for selecting the larger #2/0 conductor instead of the #1/0 conductor (during new construction or a planned replacement). It is doubtful that energy savings could justify replacement of an existing operational conductor.

Annual energy losses for different sized Army installations were calculated using the procedure outlined above. The information in Table 21 show the excess annual energy losses per feeder associated with various conductor sizes. For any given conductor, the amount of annual energy losses shown in Table 21 will be the *additional losses* caused by not using the optimally sized (baseline) conductor. The optimal conductor values for impedance were calculated for each size of installation (shown at the bottom of Table 21). Use Table 21 to determine the additional losses by assuming, for example, that DEH engineers at a small installation with an estimated optimal impedance as shown want to know how much annual energy would be lost by choosing a larger conductor (1-stranded #7). Find the listing for 1-stranded #7 listed in the table and read the annual energy loss of 30.433 kWh (0.83 percent increase in losses) in the small installation column. This is the additional loss for a small installation that does not use the optimally sized conductor shown at the bottom of Table 21.

The data listed in Table 21 generally shows that, the greater the distribution line impedance, the greater the energy loss. To minimize energy losses, the selected conductor should have the smallest impedance per mile that can handle the specified load.

The greatest energy iosses suffered by the sampling of large Army installations were apparently caused by the use of undersized conductors. These large installations in the sample data also had higher phase currents, and therefore more I^2R losses.

Table 19

Power System Parameters for Example Problem (Chapter 8)

Parameters	Measure
Effective voltage	12,470/7,200 V
Effective current	100 A
Power factor	95 percent
Percent loading	50 percent
Impedance of conductor #3/0 at 25 °C	0.35+j0.52 Ω/Mile
Impedance of conductor #2/0 at 25 °C	0.44+j0.53 Ω/Mile
Impedance of conductor #1/0 at 25 °C	0.56+j0.55 Ω/Mile

Table 20

Results for Example Problem (Chapter 8)

Total Feeder Length (Mile)	Conductor Load #1/0 AWG I^{2}R Loss (kW)	#1/0 AWG Energy Loss (kWh/yr)	#2/0 AWG I^{2}R Loss (kW)	#2/0 AWG Energy Loss (kWh/yr)	#3/0 AWG I^{2}R Loss (kW)	#3/0 AWG Energy Loss (kWh/yr)
1	8.40	36,792	6.60	28,908	5.25	22,995
3	25.20	110,376	19.80	86,724	15.75	68,985
5	42.00	183,960	33.00	144,540	26.25	114,975

This data shows that the use of optimally sized conductors can help reduce an Army installation's energy bills; however the savings gained by conductor replacement may not justify replacing every conductor on an installation at once. The best time to resize conductors to the optimum would be on construction of new feeders or replacement of worn feeders.

Table 21

Annual Energy Losses for Non-Optimal Conductors (Per Feeder)

Description of Solid Copper Conductor	Conductor Impedance Data (Ω/Mile)	Small Installation		Medium Installation		Large Installation	
		% Power Loss	Energy Loss (kWh)	% Power Loss	Energy Loss (kWh)	% Power Loss	Energy Loss (kWh)
Single Stranded Solid Copper							
1 Stranded #2	0.86+j0.58	2.99	110,150	1.35	124,534	N/A	N/A
1 Stranded #3	1.09+j0.60	2.73	100,597	1.19	109,611	N/A	N/A
1 Stranded #4	1.37+j0.61	2.41	88,762	0.99	91,122	N/A	N/A
1 Stranded #5	1.73+j0.62	1.99	73,546	0.73	67,351	N/A	N/A
1 Stranded #6	2.18+j0.64	1.48	54,525	0.41	37,638	N/A	N/A
1 Stranded #7	2.75+j0.65	0.83	30,433	0.00	0	N/A	N/A
Triple Stranded Solid Copper							
3 Stranded #1	0.69+j0.56	3.19	117,420	1.48	135,891	N/A	N/A
3 Stranded #2	0.87+j0.57	2.98	109,769	1.35	123,940	N/A	N/A
3 Stranded #3	1.10+j0.59	2.72	100,175	1.18	108,951	N/A	N/A
3 Stranded #4	1.39+j.60	2.38	87,917	0.97	89,802	N/A	N/A
3 Stranded #5	1.75+j0.61	1.97	72,700	0.72	66,031	N/A	N/A
3 Stranded #6	2.21+j0.63	1.44	53,257	0.39	35,657	N/A	N/A
Seven Stranded Solid Copper							
7 Stranded #4/0	0.28+j0.50	3.66	134,919	1.77	163,228	0.61	83,859
7 Stranded #3/0	0.35+j0.52	3.58	131,875	1.72	158,474	N/A	0
7 Stranded #1/0	0.56+j0.55	3.34	123,210	1.57	144,938	N/A	N/A
7 Stranded #1	0.70+j0.56	3.18	117,124	1.47	135,429	N/A	N/A
7 Stranded #2	0.88+j0.57	2.97	109,389	1.34	123,346	N/A	N/A
7 Stranded #3	1.11+j0.59	2.71	99,752	1.18	108,291	N/A	N/A
Multistranded Solid Copper							
1.0 MCM	0.06+j0.40	3.92	144,006	1.93	177,425	2.56	334,271
0.9 MCM	0.07+j0.41	3.91	143,753	1.93	177,029	2.50	327,283
0.8 MCM	0.08+j0.41	3.90	143,414	1.92	176,500	2.41	317,965
0.75 MCM	0.08+j0.42	3.89	143,203	1.92	176,170	2.36	312,141
0.7 MCM	0.09+j0.42	3.89	142,992	1.91	175,840	2.31	306,318
0.6 MCM	0.10+j0.43	3.87	142,400	1.90	174,916	2.17	290,012

*N/A - This conductor has a greater impedance per mile than optimal size.

Table 21 (Cont'd)

Baseline (Optimal) Values	Small Installation	Medium Installation	Large Installation
Estimated Impedance (Ω/Mile)	3.47+j0.66	2.75+J.065	0.35+KJ0.50
Estimated Phase Current	40	50	211
Annual Energy Loss for Conductor (kWh)	146,669	181,585	407,647

*N/A - This conductor has a greater impedance per mile than optimal size

9 POTENTIAL SAVINGS AT ARMY INSTALLATIONS

Overview

The energy loss reduction methods discussed in this study can help determine the estimated annual energy losses (potential energy savings) at typical Army installations. Each method can produce a measurable energy savings based on the amount of losses calculated in this report. This study did not address potential energy savings directly, but instead analyzed energy in terms of estimated losses. These losses can be converted to an energy savings by eliminating the losses from a distribution system. Some of the losses that were calculated are significant, while others are almost negligible.

The objective of this section is to combine the energy losses from each section to determine a total energy loss for typical size Army installations. The annual energy losses for the three different size installations are presented in Table 22 (small), Table 23 (medium), and Table 24 (large). For each loss reduction method, the estimated energy losses are shown for a worst, nominal (typical), and best case assumption. This allows the approximate range of expected energy losses for any particular Army installation to be estimated. The potential energy savings are estimated based on the ability of the Army installation to reduce certain energy losses by using the reduction methods.

To calculate the annual energy losses for the three different cases, the range of key parameters needed to be identified. The assumed ranges are listed in Table 25 (small installation), Table 26 (medium installation), and Table 27 (large installation). These ranges define the conditions that were assumed for the three different cases (worst, nominal, and best) at each size installation. Of the three cases, the nominal case represents numbers that would be expected to be the most realistic for most Army distribution systems that have not already undertaken loss reduction measures. The assumptions are summarized below.

Table 22

Total Annual Energy Loss Estimates (Small Army Installations)

Energy Loss Reduction Method	Small Installation Energy Losses (MWh)		
	Worst Case	Nominal	Best Case
Balancing three-phase loads	134	54	0
Balancing feeder circuit loads	197	22	0
Power factor correction	254	155	71
Optimal transformer sizing	53	27	0
Conservation voltage reduction	694	349	0
Optimal conductor sizing	368	152	0
Total annual energy loss per installation	**1,700**	**759**	**71**

Table 23

Total Annual Energy Loss Estimates (Medium Army Installations)

Energy Loss Reduction Method	Medium Installation Energy Losses (MWh)		
	Worst Case	Nominal	Best Case
Balancing three-phase loads	365	144	0
Balancing feeder circuit loads	488	54	0
Power factor correction	629	384	177
Optimal transformer sizing	266	133	0
Conservation voltage reduction	3,469	1,744	0
Optimal conductor sizing	1,096	674	0
Total annual energy loss per installation	**6,313**	**3,133**	**177**

Table 24

Total Annual Energy Loss Estimates (Large Army Installations)

Energy Loss Reduction Method	Large Installation Energy Losses (MWh)		
	Worst Case	Nominal	Best Case
Balancing three-phase loads	1,489	604	0
Balancing feeder circuit loads	2,205	245	0
Power factor correction	2,826	1,726	795
Optimal transfer sizing	798	399	0
Conservation voltage reduction	10,409	5,231	0
Optimal conductor sizing	6,685	1,677	0
Total annual energy loss per installation	**24,412**	**9,882**	**795**

Table 25

Assumed Electrical Data Ranges (Small Army Installations)

Energy Loss Reduction Method	Key Parameters	Assumed Small Installation Ranges		
		Worst Case	Nominal	Best Case
Balancing three-phase loads	% Unbalance of phases	-20%	-10%	0%
Balancing feeder circuit loads	Fault location	0.20/0.80	0.40/0.60	0.50
Power factor correction	Power factor	85%	90%	95%
Optimal transformer sizing *	% Affected transformers	50%	25%	None
Conservation voltage reduction	Voltage reduction	2%	1%	None
Optimal conductor sizing	Conductor size	1 Stranded #5	1 Stranded #7	Optimal size

* 50kVA transformer is considered optimal size for small installation.

Table 26

Assumed Electrical Data Ranges (Medium Army Installations)

Energy Loss Reduction Method	Key Parameters	Assumed Medium Installation Ranges		
		Worst Case	Nominal	Best Case
Balancing three-phase loads	% Unbalance of phases	-20%	-10%	0%
Balancing feeder circuit loads	Fault location	0.20/0.80	0.40/0.60	0.50
Power factor correction	Power factor	85%	90%	95%
Optimal transformer sizing *	% Affected transformers	50%	25%	None
Conservation voltage reduction	Voltage reduction	2%	1%	None
Optimal conductor sizing	Conductor size	1 Stranded #3	1 Stranded #5	Optimal size

* 50kVA transformer is considered optimal size for small installation.

Table 27

Assumed Electrical Data Ranges (Large Army Installations)

Energy Loss Reduction Method	Key Parameters	Assumed Large Installation Ranges		
		Worst Case	Nominal	Best Case
Balancing three-phase loads	% Unbalance of phases	-20%	-10%	0%
Balancing feeder circuit loads	Fault location	0.20/0.80	0.40/0.60	0.50
Power factor correction	Power factor	85%	90%	95%
Optimal transformer sizing *	% Affected transformers	50%	25%	None
Conservation voltage reduction	Voltage reduction	2%	1%	None
Optimal conductor sizing	Conductor size	Multistranded 1/0 MCM	7 Stranded #4/0	Optimal size

* 50kVA transformer is considered optimal size for small installation.

Percent Unbalance of Three-Phase Loads

The values used to define percent unbalance for three-phase loads were assumed based on the reasoning that a –20 percent unbalance would be the worst case encountered in a practical application; any greater unbalance would most likely cause overheating in the distribution lines. A –10 percent unbalance is assumed for the nominal case. The best case would be zero unbalance in all feeders (no losses). It is also assumed that all feeders are affected by the assumed unbalance condition.

Loop Break Location in Feeder Loads

For feeder circuit analysis, it is assumed that the best case for a looped feeder fault/break location is 0.50 (no energy losses), which means the break is exactly halfway around the feeder length. The worst practical case is assumed to be a location of 0.20/0.80. The nominal case was assumed to be where the average amount of losses would occur (0.40/0.60). Again, it is assumed that all feeders are affected for each case.

Power Factor

Power factor analysis considers the worst case to be approximately 85 percent and the best case as 95 percent. The best case determination was based on the requirement of a 95 percent power factor to avoid a power factor penalty; the worst case of 85 percent was confirmed by actual power study information available from previous distribution system evaluations. The nominal power factor is assumed to be about 90 percent. A power factor above 95 percent is possible; therefore even the best case is considered to have an energy loss. This is reflected in the results for each installation.

Transformer Size

The optimal transformer size is assumed to be 50kVA for each size installation. For the worst case, it is assumed that 50 percent of the installation's transformers are not optimally sized. The nominal case assumes that 25 percent are affected. (The best case assumes that all transformers are optimally sized.)

Percent Voltage Reduction

For conservation voltage reduction, it is assumed that the worst case will be about a 2 percent voltage reduction. The Army specifications allow a –2 percent voltage swing on the feeder, so that at most the voltage could be reduced by 4 percent. The 4 percent reduction in voltage was not assumed as the worst case because it is highly unlikely, if not impossible. The nominal case uses a 1 percent voltage reduction. The best case is a zero percent reduction in voltage (no losses).

Conductor Size

For optimal conductor sizing, it is assumed that the nominal feeder impedance (conductor) selected can still safely carry the average feeder current per-phase, but it has slightly more losses than the optimal size would have. The worst case is assumed to be a conductor a few sizes smaller (greater impedance) than the optimal size. The best case (optimal size) is where no additional energy losses occur.

The number of feeders and transformers used to calculate the estimated total losses were taken from Table 2.

The defined ranges furnish sufficient information to estimate potential energy savings that can be achieved if all the energy loss reduction methods contained in this report are implemented. However, it must be stressed that the only absolute way to determine energy losses is to perform a distribution system evaluation of the individual Army installation being investigated.

Small, Medium, and Large Installations

The results of the energy loss calculations are shown in Table 23 (small Army installation), Table 24 (medium Army installation), and Table 25 (Large Army installation). The nominal case is assumed to represent the conditions considered most typical for an electrical distribution system. However, note that the estimates will be on the high side because of the assumptions that were used.

It is doubtful that an installation can reduce energy losses by the total amount shown by the results. Some losses will always be present in a distribution system. However, by being aware of the relative magnitude of losses from various causes, it may be possible to take low-cost steps to reduce severe losses. The results shown in Tables 23, 24, and 25 show the estimated energy losses for typical installation distribution systems of different sizes. The values quantitatively show an estimate of the amount of annual energy that is currently being dissipated in the electrical distribution system. However, this energy loss could be reduced if appropriate energy saving options are either fully or partially implemented.

As stated, it is not practical to assume that the total energy losses that were calculated could be reduced 100 percent. To arrive at a more reasonable estimate of potential savings for distribution losses at an Army installation, percentage multipliers that reflect the portion of the distribution system that might be affected were subjectively selected for each loss category. The percentages were used to adjust losses from Tables 25, 26, and 27 (Nominal values). These numbers are presented in Table 28 as "ballpark estimates" of possible distribution system energy savings at Army installations that have not already taken loss reduction actions. When summing the total estimated energy saving potential in Table 28, conservation voltage reduction was listed separately because, compared to the other measures, it requires a major effort for implementation (with potential major results).

Table 28

Estimated Savings Potential

Parameter	Assumed % Implementation	Small Installation (MWh)	Medium Installation (MWh)	Large Installation (MWh)
Balancing three-phase loads	40%	22	58	242
Balancing feeder circuit loads	40%	9	22	98
Power factor correction	30%	47	115	518
Optimal transformer sizing	10%	3	13	40
Conductor sizing	20%	30	135	335
Total		**110**	**343**	**1233**
Conservation voltage	40%	140	698	2092

10 CONCLUSIONS

Engineering calculations were performed to estimate distribution system losses on a per feeder, per transformer, or per conductor basis for the following loss reduction methods:

1. Balancing three-phase loads
2. Balancing feeder circuit loads
3. Correcting the power factor
4. Optimally sizing transformers
5. Reducing voltage for conservation
6. Sizing conductors.

Based on the per feeder, per transformer, or per conductor calculations, aggregate distribution losses were estimated for a small, medium, and a large Army installation. From the aggregate installation-wide distribution losses, a sample estimate of savings potential was calculated. This savings potential was found by subjectively assuming a reasonable percentage of the losses that might be eliminated. The assumed reasonable percentage was selected to be appropriate for installations that have not undertaken loss reduction actions. Conclusions for each loss reduction method are described below.

Balancing Three-Phase Loads

From the example problem in Chapter 3, the assumed typical feeder (of 3 miles length) showed approximately 6000 kWh per year difference between the balanced condition and a moderate imbalanced condition. (At $0.05 per kWh, 6000 kWh = $300 per year per feeder cost of losses.)

On an installation-wide basis (assuming 40 percent of losses can be eliminated) as shown in Table 28, a medium-sized installation could save 58,000 kWh per year. (At $0.05 per kWh, 58,000 kWh = $2900 per year savings installation-wide.)

While savings from balancing phases are small, the efforts required to maintain balanced phases are not major. Also, and maybe more importantly, keeping phases balanced is good operating practice for distribution systems. Therefore, it is recommended that efforts be made to keep phases balanced.

Balancing Feeder Circuit Loads

From the example problem in Chapter 4, the assumed typical feeder (of 3 miles length) showed approximately 2600 kWh per year difference between the balanced condition and a moderate imbalanced condition. (At $0.05 per kWh, 2600 kWh = $130 per year per feeder cost of losses.)

On an installation-wide basis (assuming 40 percent of losses can be eliminated) as shown in Table 28, a medium-sized installation could save 22,000 kWh per year (At $0.05 per kWh, 22,000 kWh = $1100 per year savings installation-wide.)

The degree of difficulty for implementing actions to balance feeder circuit loads depends on the location of existing feeder switches relative to loads. It is suggested that distribution engineers examine feeder loading to determine whether existing switches could easily be used to balance feeder loads. If not, note the desired location for a new switch and wait for the next construction or repair at that location that might permit the economical installation of a switch.

Power Factor Correction

From the example problem in Chapter 5, the assumed typical feeder (of 3 miles length) showed approximately 28,000 kWh per year difference between the 80 percent pf condition and a 90 percent pf condition. (At $0.05 per kWh, 28000 kWh = $1400 per year per feeder cost of losses.)

On an installation-wide basis (assuming 30 percent of losses can be eliminated) as shown in Table 28, a medium-sized installation could save 22,000 kWh per year (At $0.05 per kWh, 22,000 kWh = $1100 per year savings installation-wide.)

It is recommended that distribution systems operating with a power factor below 95 percent should evaluate the economics of power factor correction, including the energy losses as described in this report in addition to any utility bill penalties.

Optimal Transformer Sizing

The calculations in Chapter 6 indicate that, in most cases, an oversized transformer will create additional losses compared to a transformer properly sized to the load without excess capacity. However, this trend was not absolute. For a few cases, the calculations indicated that a larger transformer, with an inherently better efficiency rating, actually decreased total losses. The quantity of additional losses for using an oversized transformer for a common load size such a 50kVA was 1192 kWh per year. (At $0.05 per kWh, 1192 kWh = $60 per year per transformer cost of losses.) For many other load sizes, the losses were less than half this amount. The estimate of installation-wide potential savings in Chapter 9 resulted in rather small quantity (13,000 kWh; at $0.05/kWh = $650 per year installation-wide potential savings).

Since potential savings are small, it is not suggested that retrofitting transformers to different sizes is practical. However, it is suggested that energy losses provide good reason to avoid installing oversized transformers (intentionally or unintentionally) and to disconnect transformers that are no longer needed.

Conductor Sizing

From the example problem in Chapter 8, the assumed typical feeder (of 3 miles length) showed approximately 24000 kWh per year difference between using a #1/0 conductor or using the next larger size to reduce losses. (At $0.05 per kWh, 24000 kWh = $1200 per year per feeder potential loss reduction.)

On an installation-wide basis, assuming 20 percent of losses can be eliminated (Table 28) a medium-sized installation could save 135,000 kWh per year. (At $0.05 per kWh, 135,000 kWh = $6700 per year savings installation-wide.)

It is not likely that potential savings could justify a conductor retrofit. However, when replacing conductors or during new construction, an economic evaluation should be made to determine whether the lower energy losses of the larger conductor can justify the extra material costs.

Combined Installation-Wide Potential Savings

For the five discussed loss reduction methods, the combined installation-wide potential savings are 110 MWh, 343 MWh, and 1233 MWh, for small, medium, and large installations, respectively (Table 28). At $0.05 per kWh, potential savings are estimated to be:

- small installations: $5,500 per year
- medium installations: $17,000 per year
- large installations: $62,000 per year.

Note that this does not include conservation voltage reduction, which is discussed below. Of this estimated savings, more than one third is from power factor correction, more than one fourth is from conductor sizing, and the other three loss reduction methods account for the remainder.

Since conductor (re)sizing is not likely to be practical as an economical retrofit, power factor appears to be a major focal point for reducing losses, independent of whether or not the installation pays a power factor penalty on the utility bill.

Conservation Voltage Reduction (CVR)

The example problem in Chapter 7, the assumed typical feeder (of 2 miles length) showed approximately 284,000 kWh per year for a 5.8 percent reduction in end-of-line voltage. (At $0.05 per kWh, 284,000 kWh = $14,200 per year per feeder reduction in losses.) However, the 5.8 percent voltage reduction is not a realistic assumption for installation-wide CVR. The installation-wide calculations (Chapter 9) for aggregate savings potential assumes a much more reasonable 1 percent voltage reduction.

On an installation-wide basis, assuming 40 percent of losses can be eliminated (Table 28), a medium-sized installation could save 698,000 kWh per year. (At $0.05 per kWh, 698,000 kWh = $35,000 per year savings installation-wide.)

CVR was calculated to have the greatest potential for energy savings compared to the other loss reduction methods. However, implementation requires careful engineering to avoid potentially severe consequences. Therefore, it is suggested that an installation interested in CVR should proceed cautiously. If a number of installations are interested, it is recommended that one test site be selected to implement CVR.

General Conclusions

Installation electrical engineers need to be aware of the relative magnitude and sources of distribution system energy losses. Since the potential savings for some loss reduction methods is small, specific retrofit efforts may not be economically justifiable. However, during new construction design or replacement projects, it may be feasible to incorporate some of the loss reduction methods.

This report provides general estimates of distribution energy losses and potential savings for assumed conditions that were selected as typical for numerous sites. While these estimates do not provide precise numbers for any specific site, the information in this report can: (1) help distribution engineers examine energy losses more carefully, and (2) help check the feasibility of other, more detailed efforts to quantify losses.

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